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Potential Impacts of Global Warming on Salmon Production in the Fraser River Watershed

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by

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ABSTRACT

Implications of the effects of global warming on salmonid fisheries resources of the Fraser River basin were synthesized from a literature review. While the greenhouse theory of global warming has not been substantiated definitively to date, the establishment of proactive and adaptive fisheries management policies to respond to potential climatic-induced shifts in resource distribution and productivity is warranted. In the Fraser River basin, salmon would be susceptible to climatic warming through increases in water temperatures and precipitation-related changes in flow regime; winter runoff may increase and summer runoff may decrease. Existing stock monitoring programs would provide sufficient data to detect climate change impacts. Mitigating the effects of climatic change does not appear feasible over the long term. Eight impact hypotheses developed for this report address differential effects that the various stocks of five species of salmon may encounter.

RÉSUMÉ

Les répercussions du réchauffement planétaire sur les ressources exploitées par les pêches au saumon du bassin du Fraser ont été colligées à la suite d'un dépouillement des articles afférents. Bien que l'hypothèse d'un réchauffement planétaire par effet de serre n'ait pas encore été prouvée de manière concluante, il semble justifié d'adopter des politiques de gestion des pêches qui sont de nature à nous permettre d'anticiper et de nous adapter aux changements potentiels, d'origine climatique, sur les plans de la productivité et de la distribution des ressources. Dans le bassin du Fraser, le saumon serait sensible au réchauffement planétaire par suite du réchauffement de l'eau et de changements des régimes d'écoulement associés aux précipitations : ainsi, il pourrait y avoir plus de ruissellement en hiver et moins de ruissellement en été. Les programmes de surveillance des stocks devraient fournir assez de renseignements pour permettre de détecter les répercussions d'un changement climatique. Il ne semble pas qu'on puisse atténuer à long terme les effets d'un changement climatique. Huit hypothèses relatives aux répercussions, formulées dans le cadre de ce rapport, portent sur les effets différentiels que différents stocks de cinq espèces de saumon peuvent avoir à subir.

FOREWORD

This report was commissioned by the Fraser River Environmentally Sustainable Development Task Force. The task force was established in 1990 as part of the Government of Canada's and the Department of Fisheries and Oceans' (DFO) commitments towards achieving sustainable development of our fisheries resources. The principles that guide DFO are those popularized by the 1987 World Commission on the Environment and Development - Our Common Future. This report's review of global warming should complement discussions on multi-disciplined sustainable development in the Fraser River basin.

The driving objective of the task force was to devise and complete a habitat management plan for the Fraser River. The plan must incorporate numerous considerations, including climatic change. It was recognized that salmon habitat has been significantly degraded in the Fraser River basin over the past 100 years. Despite that, the salmon stocks are being actively rebuilt towards historic levels. Obviously a link between the capability of the habitat to produce fish and stock rebuilding goals had to be established. Also, we had to begin the process of better protecting existing habitat and restoring and enhancing what is desirable within a plan that will involve more input than can be provided by DFO habitat and harvest managers.

To address this overall task a habitat Planning Unit divided the Fraser River basin into 15 Habitat Management Areas. This division was based on major river systems and salmon stocks. Individual Habitat Management Plans are being developed for these 15 HMAs to attempt to define salmon habitat status, stock status and habitat restoration and protection priorities. These are a first step towards establishing a fisheries data base for long-term environmental sustainable development discussions with other stakeholders in the basin.

Although the stock rebuilding initiative began several decades ago, it received greater priority after the 1985 Canada-U.S.A. International Agreement. Serious attempts to include habitat considerations into the process began in late 1988. In 1990, the initiative was incorporated into the National Green Plan's Fraser River initiative. It is now called the Fraser River Action Plan and is under the guidance of the newly-formed (Canada/ B.C./ municipal/ aboriginal/ public) Fraser Basin Management Board.

As part of our commitment to sustainable development and Canada's Green Plan we have defined specific goals for sustainable fisheries development. The Habitat Management Plan and associated DFO decisions and activities are guided by the goals of sustainable development, and particularly its two basic principles:

- To maintain ecological diversity of the basin; and

- To maximize the net economic benefits that can be derived from the resource.

DFO has defined seven measurable and achievable goals for sustainable fisheries development. They are as follows:

1) **Avoiding irreversible human changes to fish producing habitats.**
Avoiding alterations to fish habitat that reduce its capacity to produce valuable fish populations that cannot be reversed within a human generation.

2) **Maintaining the genetic diversity of fish stocks.**
No fish stock, however small, will be arbitrarily written off, and where possible it will be attempted to conserve and rebuild small and remnant stocks.

3) **Maintaining the physical and biological diversity of fish habitats.**
Physical and biological diversity of habitat provides fish with an opportunity to adopt alternative life history strategies, hence providing protection from natural variation.

4) **Providing a net gain in the productive capacity by habitat management.**
Ecological limits control productive capacity. Natural and self-sustaining production systems are preferred over semi-natural and artificial or non-self sustaining systems.

5) **Maximizing the value of commercial, sport and aboriginal fisheries.**
Both tangible and intangible market and extra-market values must be considered and measured in a way to permit comparison of competing uses of the fisheries resources.

6) **Maximizing the non-consumptive values of fishery resources.**
Intangible and cultural values associated with fishery resources must be given due consideration in decision making.

7) **Distributing fishery net benefits in a fair and equitable manner.**
Local communities must be involved in the decision-making process with respect to habitat conservation, enhancement and restoration, and particularly to who benefits and who pays.

It is hoped that the cautions outlined in this report will enable more effective land-use planning that will better protect aquatic habitat. The result of the application of this process should be a higher level of environmentally sustainable development. However, it is realized that what is done on a basin or regional basis may well be undone by global climate change. This report highlights the need to think in a global sense when we act on what we most often see as a local problem. This is our first attempt to put the freshwater aspects of salmonid production into a global climate change perspective.

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1. Introduction

The Fraser River is the major contributor to Canada's salmon resource and produces more salmon than any other single river system in the world. Under the Fraser River Action Plan Green Plan initiative, the federal Department of Fisheries and Oceans (DFO) is currently attempting to restore Fraser River salmon populations to historical levels of abundance, which are approximately double the recent levels. This objective will be accomplished by increasing escapement to spawning grounds, selective enhancement techniques, and vigorous habitat protection and management. In order to guide this restoration effort, DFO in 1989 established the Fraser River Environmentally Sustainable Development (ESD) Task Force to plan for environmentally and socially sustainable development of the fishery resources of the Fraser River basin. The Task Force is in the process of preparing detailed habitat management plans for 15 habitat management areas that have been identified within the Fraser River watershed. The habitat management plans will identify salmon habitat-related constraints and opportunities in the different sub-basins of the watershed.

Most fisheries habitat impacts in the Fraser River tend to be localized, specifically affecting salmon populations within discrete sub-basins of the watershed. In contrast, fisheries impacts assocated with global warming are generalized and may affect different sub-basins in similar ways. Atmospheric temperature and precipitation alterations may influence freshwater habitats by altering the aquatic temperature regime, and also by affecting stream flow discharges, both of which affect aquatic, cold-blooded organisms in fundamental ways. Significant global warming effects could also undermine existing habitat initiatives within the Fraser, e.g., allocation of water for salmon protection.

Public and scientific awareness of the environmental issues related to global warming is relatively recent. Global warming effects were not mentioned in a recent DFO Habitat Workshop which focussed specifically on habitat effects on salmonid stocks (Levings et al. 1989), nor were they mentioned as a habitat issue in a review of fish habitat issues in the Fraser River (Birtwell et al. 1988). Yet from a salmonid production perspective, global warming may represent a potentially serious fisheries habitat impact within the Fraser River watershed.

The present study was commissioned by the Fraser River ESD Task Force to identify fisheries habitat impact concerns related to global warming, and to recommend strategies for detecting and responding to future climate changes as they occur. The study emphasizes the five species of Pacific salmon, and is restricted to a consideration of impacts on the freshwater life history stages. Since global warming will likely cause future increases in sea level and alterations in oceanographic conditions in the North Pacific during the next century, marine effects on Fraser River salmon need to be also addressed at a future date. The project was designed to

address global warming issues in a qualitative manner, and to serve as a precursor for future quantitative and empirical studies. The study also considered possible monitoring strategies to detect warming impacts when they occur, and the development of a proactive strategy which anticipates salmon population responses in the Fraser River watershed.

Specific objectives of the study are: 1) to review available climate warming literature as it pertains to fish and fish habitats; 2) to summarize projected aquatic habitat effects in the Fraser Rver watershed; 3) to identify which species of Fraser River salmon might be vulnerable to global warming effects at which life history stages; 4) to define impact hypotheses which articulate possible mechanisms through which global warming effects might impact vulnerable stocks; and 5) to elaborate a series of management recommendations.

2. Literature Review

There is a large body of knowledge concerning global warming and the possible impacts upon freshwater resources, including fish populations. This literature review summarizes general aspects of global warming, together with the anticipated impacts on freshwater environments. Next, relevant aspects of fish thermal physiology and ecology are reviewed in order to predict how fish, particularly cold-water salmonids, might respond both functionally and numerically to the anticipated alterations in freshwater habitats. Recent studies which evaluate future climate warming effects on fish populations, are summarized to analyse present understanding of the topic. Lastly, the different policy options for dealing with climate warming impacts on fisheries are reviewed and summarized.

Global Warming and the Greenhouse Effect

Global warming is presently regarded by environmental scientists and policy makers as a major, international environmental issue. Hare (1988) stated his view that the greenhouse effect is currently the most important environmental problem facing the world. Another prominent climatologist (Schneider 1989A) has recently asked the question: Are we entering the greenhouse century? Due to the direct linkages between climate, ecosystems, and economic systems, global warming is presently a critical policy issue for all levels of government. This section of the literature review examines the case for global warming, considers the likely mechanisms involved, and describes some of the uncertainties in projecting the global climate of the future.

Rigorous analysis of the world's historical temperature record independently by scientists in the U.S. (Hansen 1989) and the U.K. (Jones and Wigley 1990) provides unequivocal evidence for global warming over the past century (Figure 2.1). Over this time period, the mean global surface air temperature has increased by about a half a degree Centigrade. Jones and Wigley (1990) summarize the process of generating reliable estimates of mean global temperature based on diverse and disparate temperature records. Mean global temperature data sets show that the rising temperature trend over the past century was interrupted by a cooling spell between 1940 and 1970. Since 1970, the warming trend has continued unabated (Figure 2.1).

One feature of the global surface air temperature data set that complicates the interpretation of warming trends is the large degree of seasonal and year-to-year variation observed in the data set (Figure 2.2), and the occurrence of climate variations on longer time scales, e.g., the El Niño/Southern Oscillation (ENSO) warming episodes. When the global temperature record is corrected for ENSO events, the warming trend of the late 1980s stands out prominently; in the corrected data set 1989 becomes the warmest year on record, and 1988 and 1987 are second and third, respectively (Jones and Wigley 1990). There can be little doubt that global warming is a fact of the 20th century.

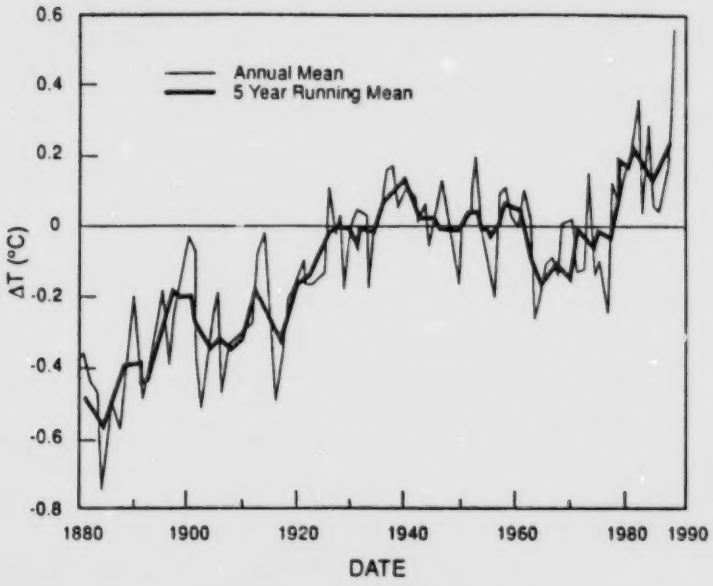

Figure 2.1. Mean global surface air temperature change for the past century, with the zero point defined as the 1951-1980 mean. Redrawn from Hansen (1989).

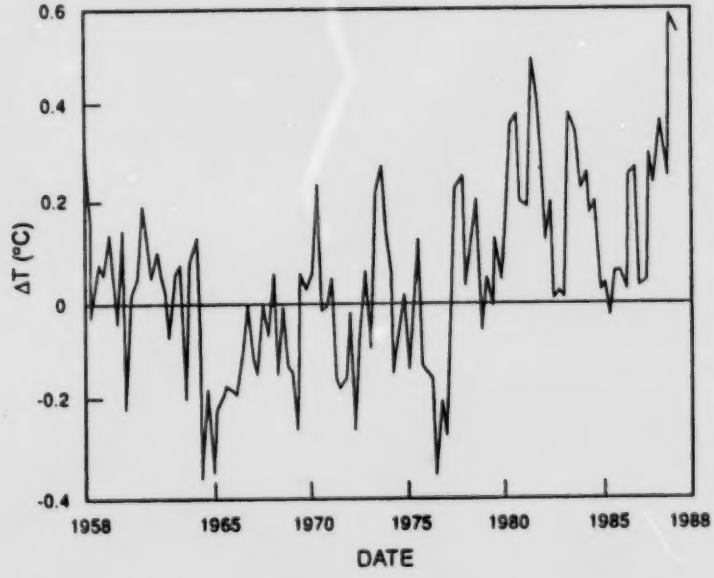

Figure 2.2. Global surface air temperature at seasonal resolution for the years 1958-1987. Redrawn from Hansen (1989).

The greenhouse effect is the result of the heat-trapping properties of trace gasses within the Earth's atmosphere. Most of the atmospheric gas, notably nitrogen and oxygen which make up 99% of the volume, are essentially transparent to solar and terrestrial radiation (Hare 1988). However, the so-called greenhouse gases (including water vapour, carbon dioxide, nitrous oxide, ozone and methane) effectively absorb infrared radiation in the 8.5 to 12.5 μm wavelength region (Figure 2.3). Due to the greenhouse effect, the surface of the earth is on average 33 °C warmer than it would be in the absence of such an effect (Schneider 1989B). Calculation of the combined radiation-trapping effect of the different greenhouse gases, and prediction of the warming effects associated with changing greenhouse gas concentrations, is complicated by a variety of factors (MacDonald 1989).

There are great disparities in the heat-trapping properties of different greenhouse gases. Halocarbons (CFCs), for example, are present in the atmosphere in extremely low concentrations, but can be extremely effective infrared absorbers, with about 10,000 times the infrared retension capacity of carbon dioxide (Blake 1989). For comparative purposes, most climatologists express greenhouse gas concentrations as "carbon dioxide equivalents".

There is good empirical evidence that the atmospheric concentrations of carbon dioxide (and other greenhouse gases) have increased over the past century, and particularly, over the past several decades (Figure 2.4). These increasing concentrations are almost certainly the result of anthropogenic activities associated with industrialization, present agricultural practices, and fossil fuel use (Figure 2.5). Global carbon dioxide emissions are presently increasing exponentially by about 0.4% per annum (Abrahamson 1989).

From an environmental perspective, critical global warming issues include the following: 1) To what extent is the observed increase in the global temperature record causally related to the observed increase in greenhouse gas concentrations? 2) How might the future global climate change in view of the projected future increases to greenhouse gas concentrations? 3) What are the implications of global climate change for the Earth's ecosystems? 4) What policies should be adopted at present, in view of the current understanding of global warming, and the uncertainties in future projections?

<u>1) To what extent is the observed increase in the global temperature record causally related to the observed increase in greenhouse gas concentrations?</u>

On time scales of both thousands of years, as well as decades, carbon dioxide and temperature are very closely correlated (Schneider 1989B). Recent studies, relying on time-series analysis methods, confirm that atmospheric carbon dioxide and temperature are significantly correlated over the past thirty years, with a time lag (in carbon dioxide content) of about five months (Kuo et al. 1990). However, as

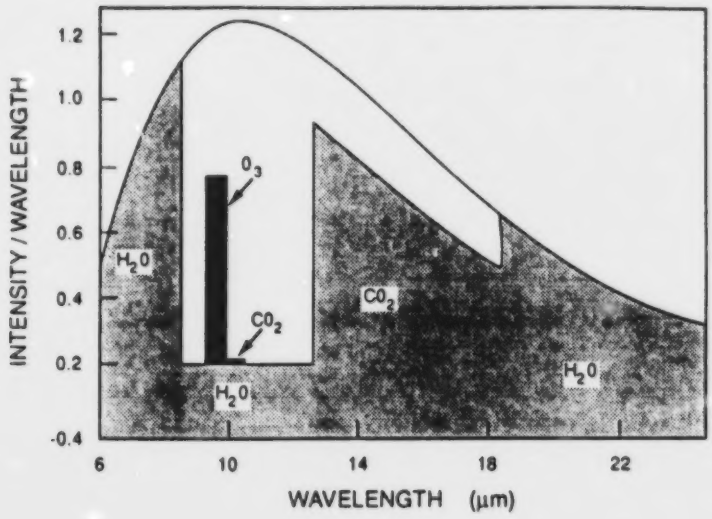

Figure 2.3. Absorption of the earth's thermal emissions by the atmosphere at a temperature of 290°K. Redrawn from MacDonald (1989).

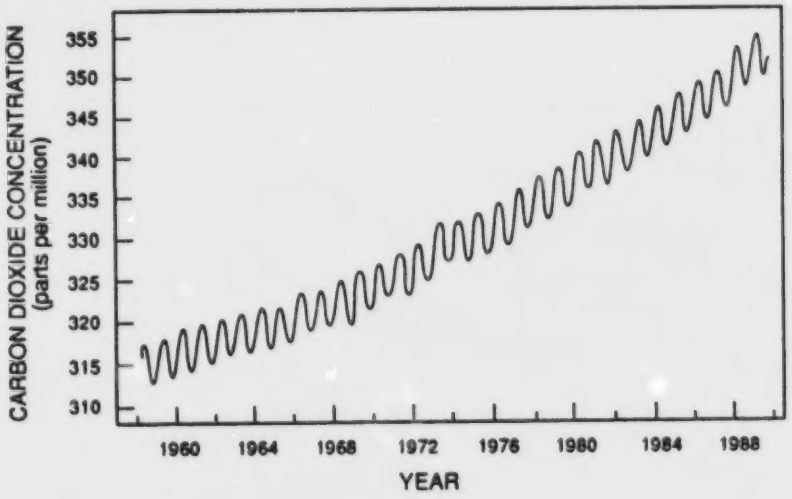

Figure 2.4. The rise in atmospheric carbon dioxide over the past 30 years. Fluctuations reflect seasonal uptake of CO_2 by temperate zone plants during the summer growing season. Data collected by C.D. Keeling and associates at the Mauna Loa observatory in Hawaii. Redrawn from White (1990).

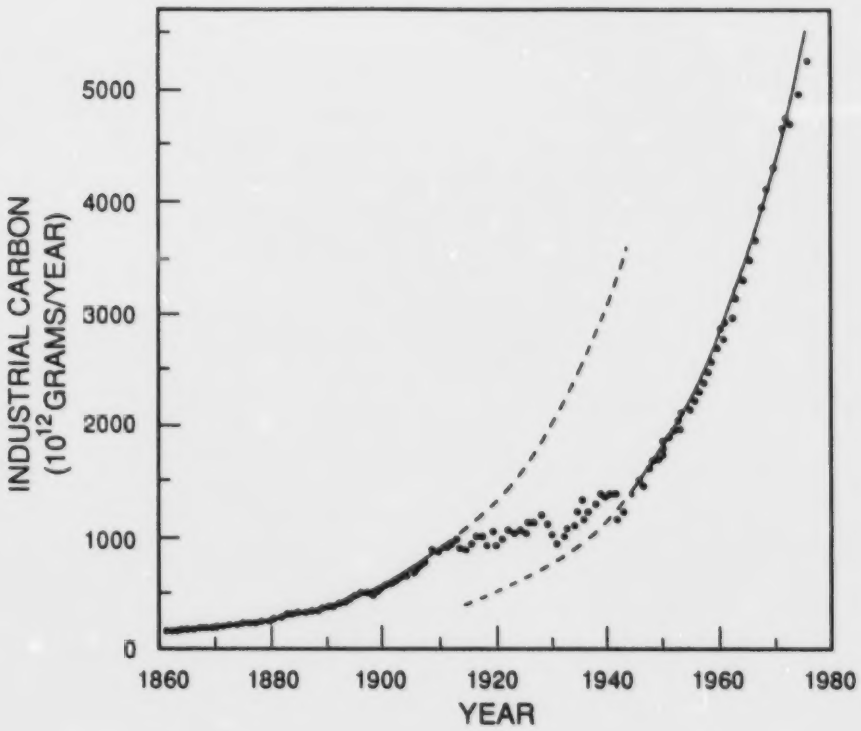

Figure 2.5. Anthropogenic carbon dioxide production rate from 1860 to the present. The deviations from exponential growth between 1914 and 1945 reflect the effects of the two world wars and the worldwide economic chaos between the wars. Redrawn from MacDonald (1989).

statisticians frequently emphasize, use of apparent correlations to postulate causality can sometimes be misleading even if there are plausible mechanisms linking two sets of observations.

Alternative mechanisms can be invoked to account for global warming, independently of the greenhouse effect. These include factors such as a shift in the Earth's orbit or tilt-axis, solar variation, and volcanic eruptions, all of which can directly influence global climate. Many of the characteristics of the historical temperature record, including the observed cooling between 1940 and 1970 (even as concentrations of greenhouse gasses were rapidly increasing) are in conflict with the greenhouse theory (Jones and Wigley 1990).

If the greenhouse theory is correct, the predicted warming effect is great enough that the future signal (mean global temperature) should soon be large enough to detect against the background of natural climate variability (Ramanthan 1988). Coupled with improvements to existing technology for the measurement of greenhouse effects (e.g., Raval and Ramanathan 1989), climate warming predictions should be definitively realized within the (geologically) short time span of a decade-or-two.

2) How might the future global climate change in view of projected future increases to greenhouse gas concentrations?

There are several different methods available for predicting the climatic impacts of future increases in greenhouse gases. These include comparisons of climatic conditions during warm and cold periods, as well as computer simulation of future conditions with global circulation models (GCMs). Predictions from both methods are reasonably close, and there is good agreement in the results from different GCMs.

Results of the comparative method are provided by Wigley et al. (1980) who contrasted global temperature and precipitation conditions during the five warmest years in the period 1925-74, with the five coldest years during this period. Results of this analysis (Figure 2.6) suggest a latitudinal effect on the altered temperature distribution such that the variation increases in a poleward direction (greatest at the poles, least in the tropics). There are also large impacts on the distribution of precipitation changes from warm to cold years (Figure 2.7), with decreases in precipitation observed over much of the U.S., Europe and Russia, and increases in precipitation over India and the Middle East. Wigley et al. (1980) provide a cautionary note that these results are scenarios and do not provide truly valid predictions. Nevertheless, they are instructive in pointing out the possible direction of climate change associated with warming, and may actually be conservative, in view of the fact that they represent a relatively small change (0.6°C) in hemispheric mean temperature compared to an expected change of ≈ 2-5°C associated with a future doubling of atmospheric CO_2 concentration.

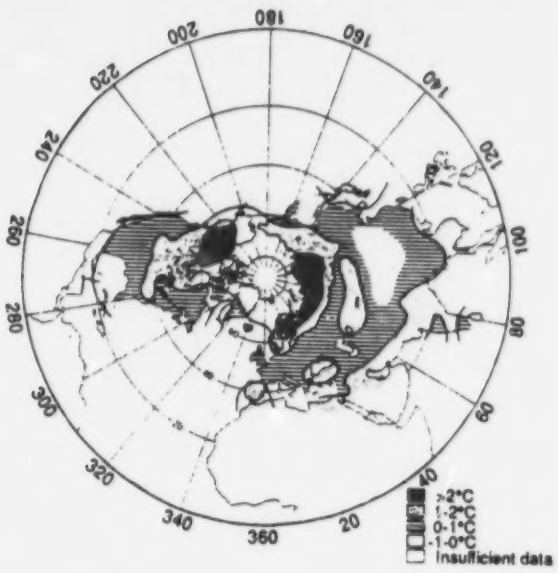

Figure 2.6. Mean annual surface temperature changes from cold to warm years between 1925 to 1974. Reproduced from Wigley et al. (1980).

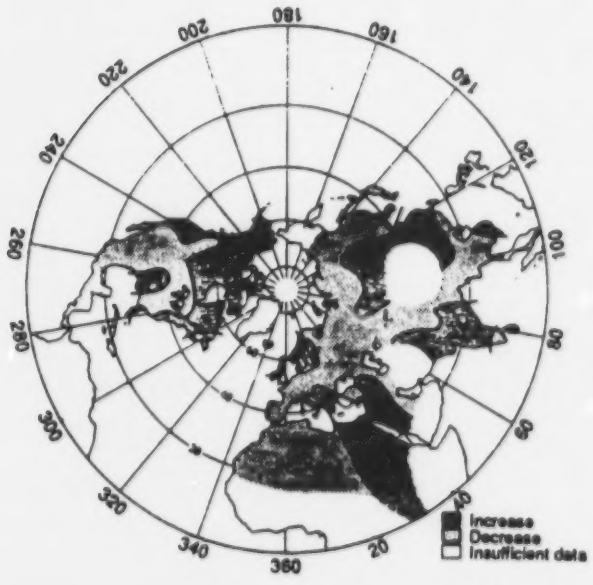

Figure 2.7. Mean annual precipitation changes from cold to warm years between 1925 to 1974. Reproduced from Wigley et al. (1980).

A review of GCMs and their predictions is provided by Kellogg (1990) who compared the results of five advanced climate models developed by NCAR (National Center for Atmospheric Research), GFDL (Geophysical Fluid Dynamics Laboratory), GISS (Goddard Institute for Space Studies), OSU (Oregon State University), and UKMO (United Kingdom Meteorological Office). The models represent the atmosphere as a three-dimensional grid with an average horizontal spacing of several hundred km, and an average vertical spacing of several km (Schneider 1989B). Even at this level of reduction (climate is calculated only at the intersections of the grid lines), the GCMs challenge the processing capability of the fastest available supercomputers.

Most climate modellers use a scenario of a future doubled "equivalent CO_2" concentration (compared to pre-industrial concentrations) in the Earth's atmosphere as a standard scenario. At present exponential rates of CO_2 increase (0.4% per annum), CO_2 concentrations will double the pre-industrial level by about the year 2030 (Smith 1990A). The time scale for such a doubling in atmospheric concentration depends on biogeophysical (e.g., response of the oceans) as well as human factors (e.g., future use of fossil fuels) which are not entirely predictable. The effect of this uncertainty in the doubling period is to shift the timing of the GCM predictions. Other major uncertainties with current global climate models are associated with ocean heat uptake rates, effects of cloud cover, high latitude responses associated with snow and ice formation, and surface hydrological processes (Dickinson 1989).

Comparison of GCM predictions led Kellogg (1990) to conclude that most climate models behave roughly in the same way during warm periods (especially in summertime). One of the models (NCAR) has been used to successfully hindcast known precipitation changes that were responsible for the reduction in North African lake levels (Kutzbach and Street-Perrott 1985), consistent with the historical evidence. Kellogg (1990) concludes that, in spite of their shortcomings, the GCMs give a reasonable picture of the future climate on an Earth warmed by the greenhouse effect. A possible scenario, based on GCM results and showing future trends in global mean temperature, is shown in Figure 2.8.

3) What are the implications of global climate change for the Earth's ecosystems?

This question is particularly relevant for north temperate regions like Canada since most GCMs predict that global warming effects will increase towards the poles (Figure 2.8). Rowe and Rizzo (1990) rephrase the question of how climatic change will affect Canadian ecosystems as follows: *"What is likely to happen to sectors of the ecosphere when they experience sudden and drastic interglacial warming; that is, when they are caught in a heat trap for which they are neither adapted nor pre-conditioned?"*

The implications of climate warming for both aquatic and terrestrial ecosystems are major, even if they are not presently well understood. Temperature and climate are

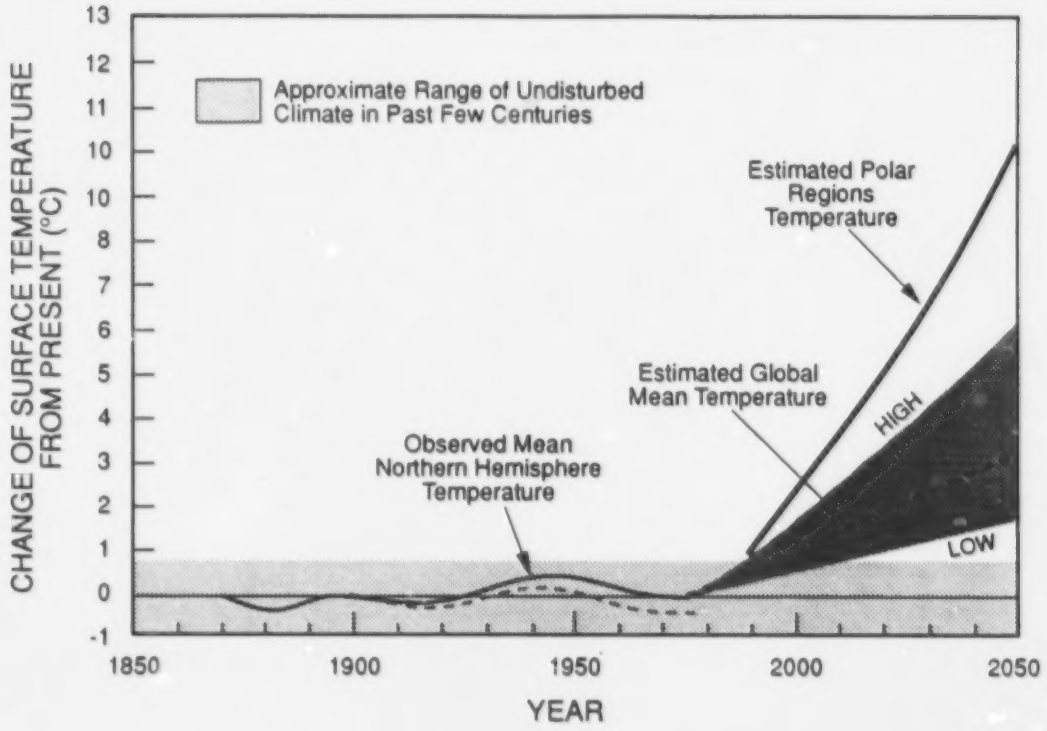

Figure 2.8. Past and future globally averaged temperature and estimated polar regions temperature. The dashed line indicates the temperature record that might have taken place if there had not been greenhouse gases added to the atmosphere. The dark shading indicates the range between a "high" and "low" scenario of fossil fuel use. The temperature scenario assumes that a doubling of the greenhouse gases will occur around 2050 AD for the dotted "estimated global mean temperature" curve. Redrawn from Kellogg (1990).

environmental variables which affect the distribution and abundance of organisms in fundamental ways; both large- and small-scale shifts in species distribution patterns would seem highly likely. There will be a high degree of uncertainty in predictions of the effects of climate alterations on populations, communities and ecosystems, and attempts to understand, anticipate, and plan for such changes have only begun recently.

For climate change impact evaluations, one of the major challenges is to generate realistic local climate change scenarios. This is a recognized weakness of existing GCMs (Smith 1990A); while the models are capable of producing reasonable climatic predictions over large spatial scales, they generally fail when applied to local, high-resolution spatial scales. Pitman et al. (1990) show that using GCMs for regional-scale impact studies of greenhouse warming can be misleading. Cohen (1990) has pointed out that there are a number of unresolved issues concerning interpolation procedures for deriving regional GCM predictions. In general, the smaller the study area under consideration, the greater is the risk that the climate scenario will not truly reflect the output of the GCM upon which it is based.

Even if realistic local, regional-scale climate change predictions can be obtained, ecological responses may be difficult to predict accurately. This is a reflection of the (generally poor) current understanding of climate-ecosystem interactions. In future, it may prove beneficial to select and monitor particular organisms as biological indicators for climate change. This strategy might be advantageous in the event that future climate change impacts occur as radical, abrupt shifts or "surprises" (Broecker 1987) either in the physical environment or within ecosystems themselves.

4) What policy initiatives should we now adopt in view of the present understanding of global warming, and the uncertainties in future projections?

Adoption of sensible policies for dealing with global warming is currently the subject of much discussion and debate, and the topic was considered in depth at the Rio "Earth Summit" which took place in June, 1992. As a means to stabilize the global climate, the 1988 Toronto Conference on The Changing Atmosphere called for a reduction in CO_2 emissions by approximately 20% of 1988 levels by the year 2005 as an initial global goal. This recommendation has not yet been adopted, and global CO_2 emissions have increased substantially since 1988. The subject is complex since there would need to be an international atmospheric convention, analagous to the Montreal Protocol designed for atmospheric ozone protection, for the measures to be effective.

There appear to be three possible policy responses: mitigation, adaptation, and prevention. Mitigation would include technical measures to counteract global warming, for example by deliberately spreading dust in the upper atmosphere to reflect sunlight,

or to fertilize the oceans with iron and so increase phytoplankton photosynthesis and CO_2 absorption. Schneider (1989B) points out the undesirability of the mitigation approach due to its reliance upon untested "technical fix" schemes whose large-scale effects are more unpredictable than climate warming itself. Adaptation includes both passive (react to events as they unfold) and active (plan for climate change) policies. The development of flexible and efficient water management systems is an integral component of an active adaptation policy (Schneider 1989B). Prevention implies curtailing the buildup of greenhouse gases. There are a number of potential strategies that could achieve this, including the allocation of tradable CO_2 emission rights to individual nations (Flavin 1990). As well, there are a number of immediate "no-regrets" policy initiatives that can be adopted in the short-term, e.g., pursuing energy efficiency, investing in alternate energy sources, undertaking reforestation programs, which can generate other environmental and economic benefits in the event that global warming predictions are incorrect.

The Brundtland Commission developed the concept of sustainable development as a means for coping with world population growth, and the 5- to 10-fold increase in the productive capacity of the world's agriculture and industry that will be required in order to feed, clothe, house and meaningfully employ an additional 5-9 billion people by the middle of the next century. The potential climatic impact associated with this human activity would seem to justify Hare's (1988) view that the greenhouse effect is the most serious environmental problem currently facing the world.

Freshwater Effects of Global Warming

Water-related issues (e.g., supply, treatment, conservation and utilization) will likely be among the predominant resource management issues of the 21st century, even in the absence of greenhouse-induced global warming effects. Virtually every economic sector is reliant upon water to some degree, and those sectors which are highly dependent (e.g., forestry, agriculture, fisheries) will be extremely susceptible to regional global warming impacts. Climatic alterations in temperature and precipitation distribution will directly influence seasonal runoff timing and volume, particularly affecting watersheds where there is currently a close balance between water demand and water supply. Planning studies have recently been undertaken to develop sustainable water management policies in the face of possible global warming, on international (Nemec 1988), national (Revelle and Waggoner 1989), and regional spatial scales (e.g., Cohen 1986, Lettenmaier and Gan 1990). Possible impacts of global warming on water resource management are both complex and far-reaching (Williams 1989).

Changes in runoff associated with different temperature or precipitation change scenarios can be easily calculated (e.g., Revelle and Waggoner 1989). Figure 2.9 shows that for a given precipitation level, increased temperatures are associated with

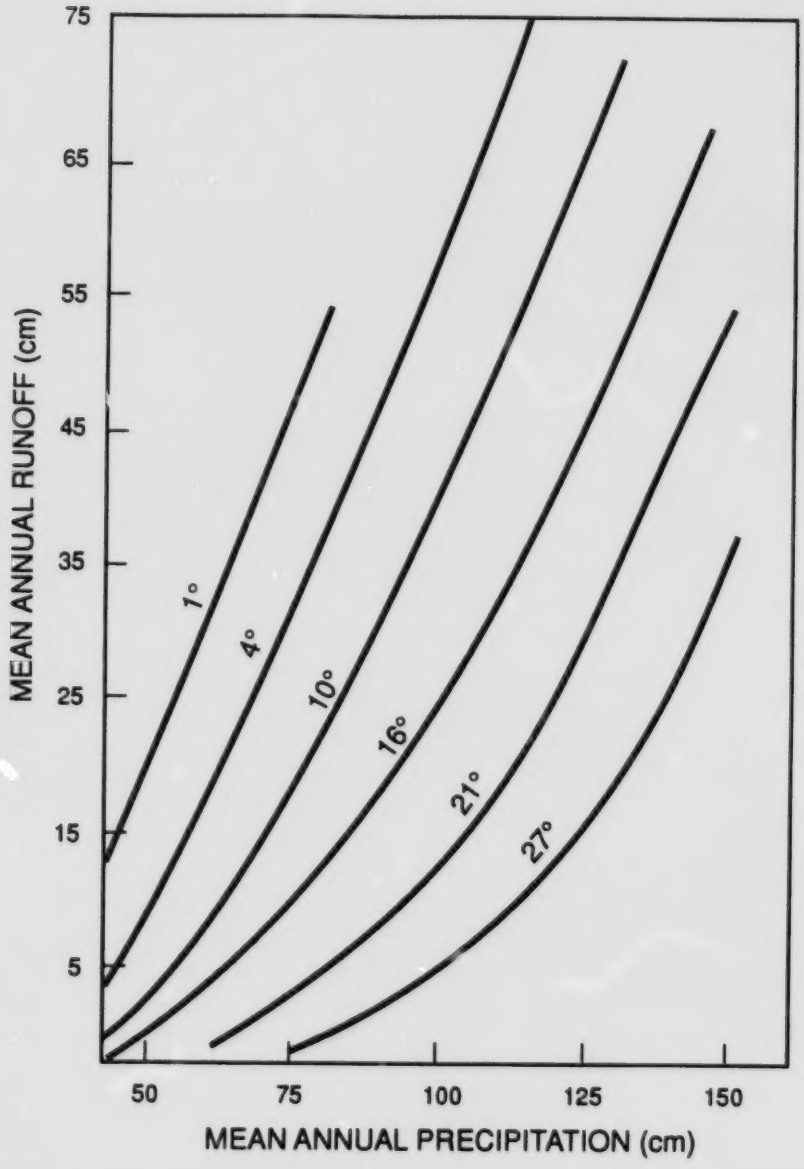

Figure 2.9. Relationship between mean annual air temperature (°C), precipitation, and runoff in 22 different basins in the United States and Canada. Redrawn from Regier and Meisner (1990).

decreased annual runoffs (other variables held equal). Nemec (1988) distinguishes between runoff availability, and water as a resource, i.e., delivered at the time and place required, in a suitable quantity and quality. For aquatic life in temperate and polar climates, seasonal cycles in water availability and temperature can influence life history events and biological production. Aquatic organisms in these regions will be sensitive to global warming impacts, especially since global warming effects will be amplified in higher latitudes during fall, winter, and spring seasons (Hengeveld 1990).

Empirical relationships (reviewed below) relating air temperature and stream/lake surface temperature suggest that water temperatures in lakes and streams will increase in response to climate warming. However, the effect of atmospheric warming will be most pronounced in rivers and streams (Meisner et al. 1987). This is because heat transfer from air is greater in rivers than lakes due to constant mixing and the relatively high air/water interface area. In lakes, direct transfer of heat from air is minor compared to that due to solar radiation, and thermal structure may be affected more by changes in variables such as humidity and wind, than by changes in air temperature (Meisner et al. 1987).

General effects of climate change on Canadian water resources are summarized by Ripley (1987), Lewis (1989) and Hengeveld (1990). Ripley (1987) reviews the results of different GCMs under a doubled CO_2 scenario and applies the UKMO (United Kingdom Meteorological Office) GCM to the Canadian climate. Results of a doubled CO_2 scenario on mean annual temperature and precipitation are shown in Figures 2.10 and 2.11, respectively. This model predicts a general 2-3°C average increase over most of Canada, with warming impacts most extreme in the central part of the country during the winter. Associated with higher temperature, the UKMO GCM predicts a 90 mm global precipitation increase, with large changes in many tropical and subtropical areas. The main mid- and high-latitude change is a wintertime increase exceeding 2 mm $\cdot$ d^{-1} centered over British Columbia and Alaska. By combining the projected temperature and precipitation conditions with a data on mean annual evapotranspiration (Figure 2.12), Ripley (1987) estimated a possible 29% increase in runoff for the Pacific drainage basin.

Of consequence for fish production, the scenario described by Ripley (1987) suggests a substantial increase in winter precipitation, coupled with possible reductions during the summer, resulting in greater seasonal fluctuations in water levels in rivers and lakes. Moreover, because of increases in predicted snowpack for the Rocky Mountain drainage, combined with earlier and more rapid springmelt, there will be significant flow effects on rivers that drain this region of the country, including the Fraser River.

Such scenarios need to be interpreted cautiously, particularly when applied on regional spatial scales. For example, comparisons of soil moisture sensitivity to doubled CO_2 concentration predicted by five GCMs are qualitatively different in winter and summer (Kellogg and Zhao 1988); in summer there may be a tendency to drier conditions in

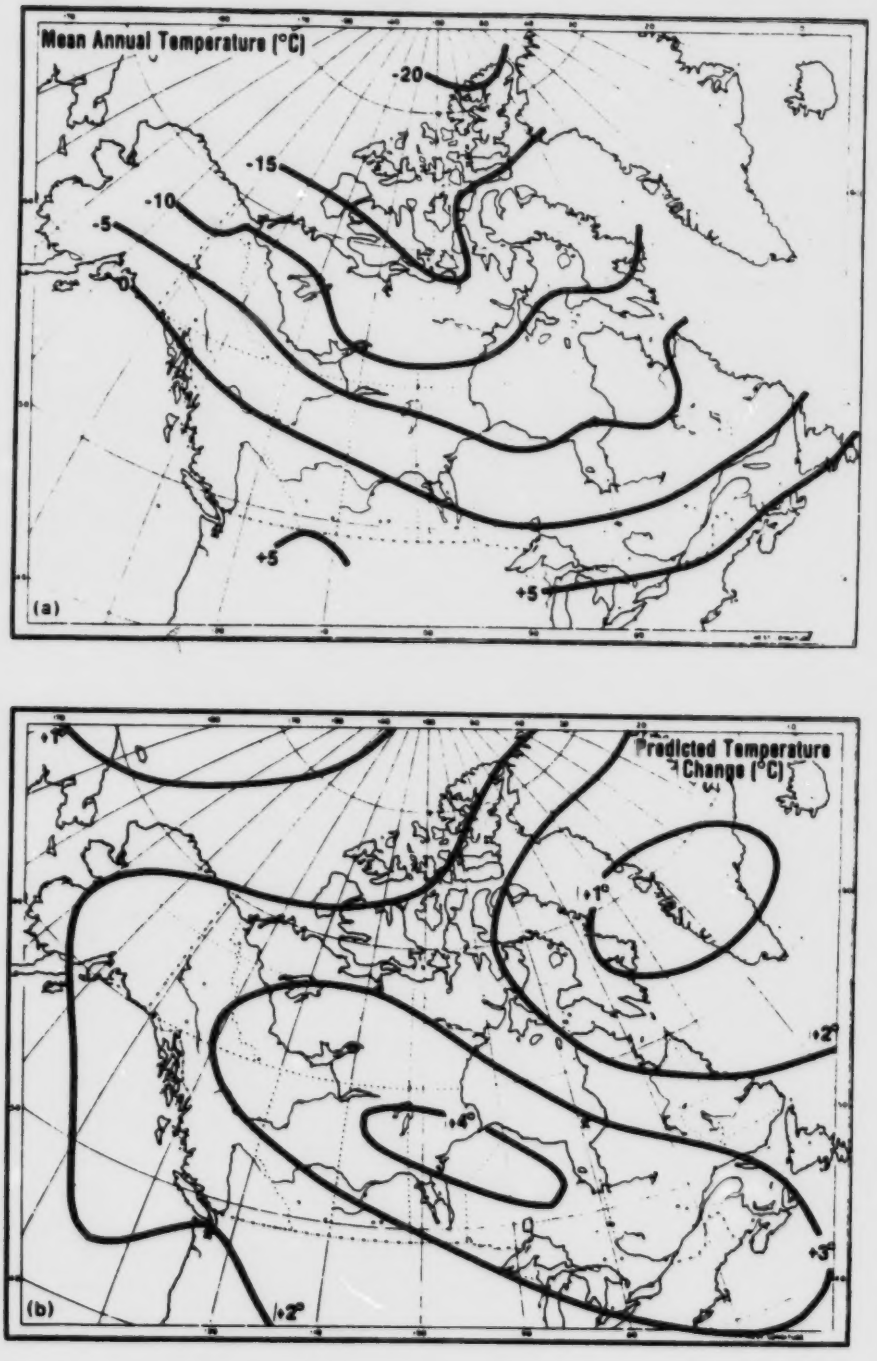

Figure 2.10. (a) Present geographical distribution of mean annual temperature in Canada; (b) UKMO model prediction of mean annual temperature change (2085-1985) for Canada. Reproduced from Ripley (1987).

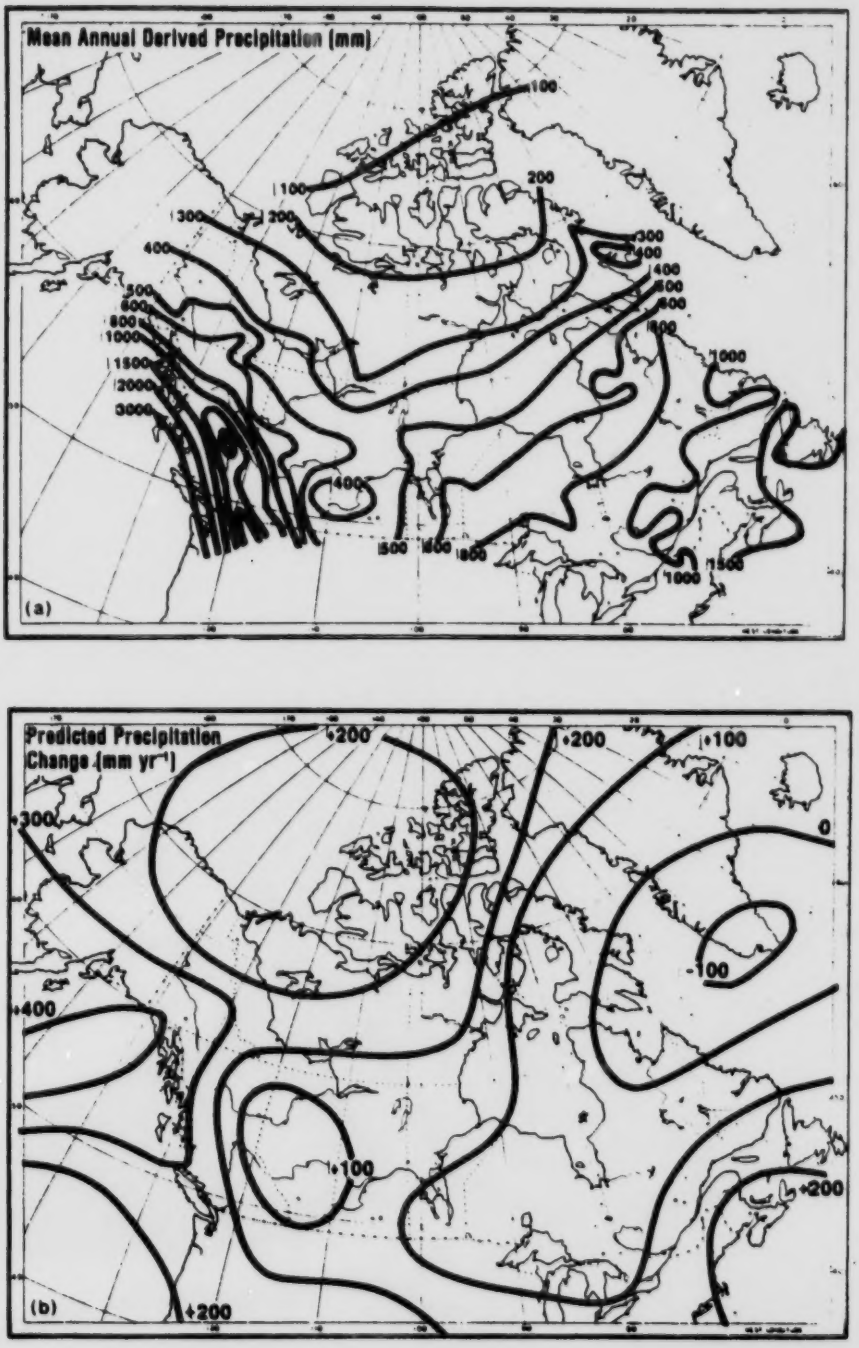

Figure 2.11. (a) Present geographical distribution of mean annual precipitation in Canada; (b) UKMO model prediction of mean annual precipitation change (2085-1985) for Canada. Reproduced from Ripley (1987).

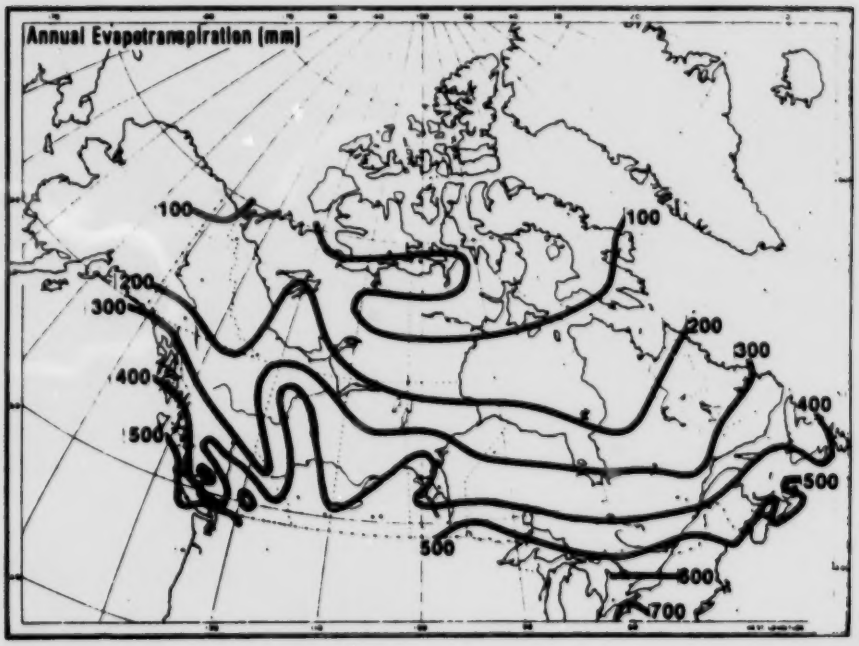

Figure 2.12. Present geographical distribution of mean annual evapotranspiration in Canada. Reproduced from Ripley (1987).

the middle of the continent where slightly increased precipitation does not compensate for increased evapotranspiration under high temperatures. Although higher temperature increases evapotranspiration, higher CO_2 concentration may have the reverse effect by causing the stomata of plants to close, decreasing their rate of transpiration, and increasing their water use efficiency (Wigley and Jones 1985). Reduced evapotranspiration would make more water available as runoff and offset the effects of CO_2-induced reductions in precipitation, or amplify the effects of precipitation increases.

In general, evidence from paleodata for a previous warm period (about 6000 - 8000 yr. B.P.), indicates that small global surface air temperature changes can cause very large changes in global water resource and vegetation patterns (Hengeveld 1990). Regional hydrological impacts of altered rainfall are substantial; a 25% decrease, for example, can decrease runoff by 80% in dry temperate regions, by 60% in wet temperate regions, and by 70% in wet tropical regions (Nemec 1988).

Particular river basin morphometric features will strongly influence river basin responses to global warming. Wigley and Jones (1985) show that for rivers with low runoff ratios (defined as the relative volume of runoff/precipitation), small changes in precipitation may cause large changes in runoff (Figure 2.13). Since most temperate rivers have runoff ratios around 0.4 (the Fraser River is probably in this vicinity), small changes in precipitation will equate to large-magnitude changes in runoff volume, assuming a maximum direct CO_2 effect on evapotranspiration (Figure 2.13). Both the amount and variability of streamflow have a direct influence on biotic community structure (Poff and Ward 1989).

Within several important North American watersheds, specific studies have been undertaken to predict regional hydrological impacts associated with future climate warming, including studies on the Great Lakes, and the Sacramento-San Joaquin River basin in California. All five GCM scenarios for the Great Lakes considered by Cohen (1986) predicted decreases to the net basin water supply of between 4-21%, depending upon the GCM and the simulation assumptions (particularly with respect to winds). This projected decrease to the water supply could potentially impact shipping, hydropower production, recreation, wildlife, and water delivery systems.

Because of the close balance between current demand and supply, any future climate-induced water shortages in the Sacramento-San Joaquin watershed might have severe consequences for local water users (which include metropolitan Los Angeles). Three key water management issues were identified by Riebsame and Jacobs (1988) as especially sensitive to climate change, including water supply and flood control, land use and levee maintenance in the Sacramento-San Joaquin delta, and water quality in the delta (related to saltwater intrusion). The hydrologic sensitivity of four mountainous catchments within the Sacramento-San Joaquin watershed was analysed by Lettenmaier and Gan (1990), using several different GCMs and a CO_2 doubling

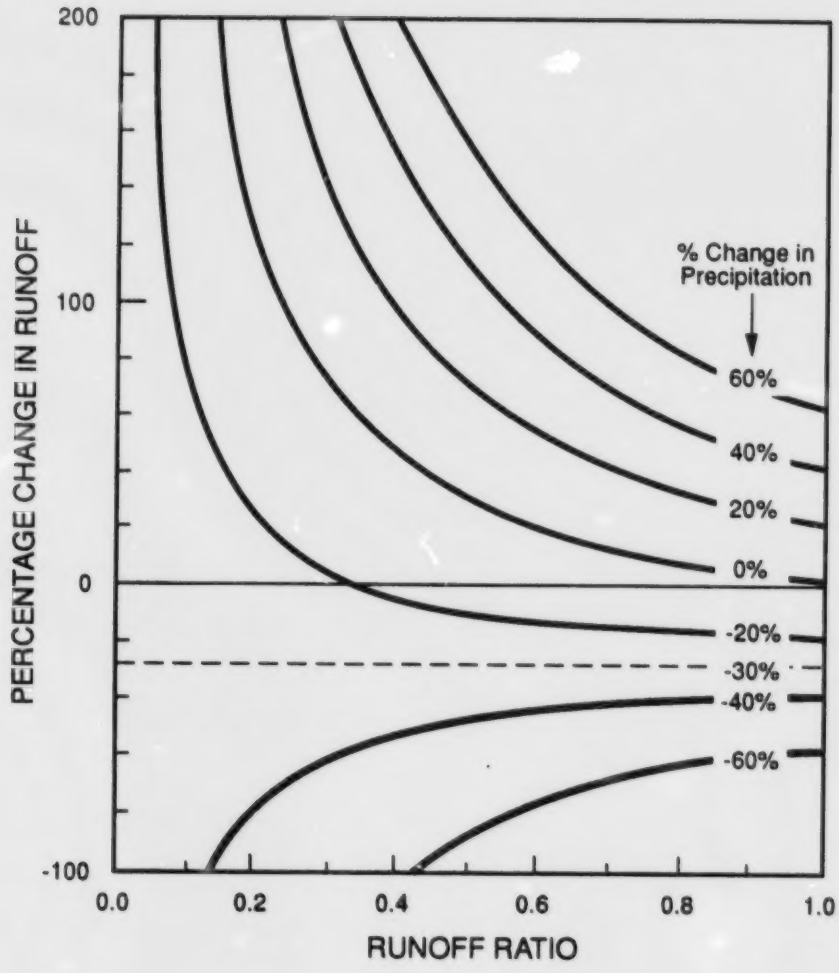

Figure 2.13. Runoff changes due to changes in precipitation assuming a maximum direct CO_2 effect on evapotranspiration. Redrawn from Wigley and Jones (1985).

scenario. The study showed that the hydrological response in the catchments was dominated by temperature-related changes in snowmelt; these had a much greater effect than the relatively modest precipitation changes simulated by the GCMs. The following conclusions were derived: 1) CO_2 doubling would decrease the average snow accumulations; 2) reduction in the amount of precipitation occurring as snow would increase winter runoff and decrease spring and summer runoff; 3) increased precipitation occurring as rainfall in the winter months would increase winter soil moisture storage and would make more moisture available for evapotranspiration (ET) in the early spring; increased temperatures would increase spring ET; 4) the reduction in moisture supply as snowmelt in the spring, coupled with increased spring ET, would reduce late spring, summer, and fall soil moisture, which would in turn reduce runoff during those periods; and 5) the specific nature of the hydrologic change would depend upon physiographic characteristics of the catchment (notably the area-elevation distribution) as well as the geologic and topographic features that control the precipitation-runoff response. In spite of the final conclusion, Lettenmaier and Gan (1990) state that their results are somewhat generalizable to other western U.S. rivers which derive a large part of their annual runoff from spring snowmelt. Presumably, the Fraser River watershed will also respond to climate warming in a similar fashion, since a large proportion of its runoff is derived from snowmelt.

Within lake environments, the distribution of heat energy strongly influences chemical and biological processes. The annual heat cycle of a lake reflects the balance between heat gain and loss, and is mainly a function of climate, geography, and mean depth (Goldman and Horne 1983). A direct relationship has been described between mean monthly surface water temperature and mean monthly air temperature for lakes Huron, Opeongo, and Mendota (McCombie 1959). Within Lake Ontario, there is a relationship between the April 1 lake temperature in deep water, and the mean air temperature measured at Pearson Airport during the preceding December-March period (Rodgers 1987). Shuter et al. (1983) provide regression relationships between mean annual surface water temperature and the number of ice-free days for a specific lake from data on the lake's long-term mean annual air temperature, its mean depth, and its fetch. For temperate zone lakes, both the number of ice-free days and the maximum surface water temperature can be predicted from mean annual air temperature, as shown on Figure 2.14. These limnological studies all imply that global warming will likely have a direct impact on lake temperatures and heating processes. Increased temperatures can also potentially influence dissolved oxygen concentration and contribute to hypoxic conditions, as occurred within the hypolimnion of Lake Erie during an anomolously warm year (Schertzer and Sawchuk 1990).

A possible preview of the possible impacts of global warming on lake physics, chemistry, and biology is available in a recent report by Schindler et al. (1990). These investigators monitored Lake 239 in the Experimental Lakes Area of Northern Ontario (an area with substantial anticipated summer greenhouse effects) for over 20 years, during which time both air and lake temperatures increased by 2°C, and the length of

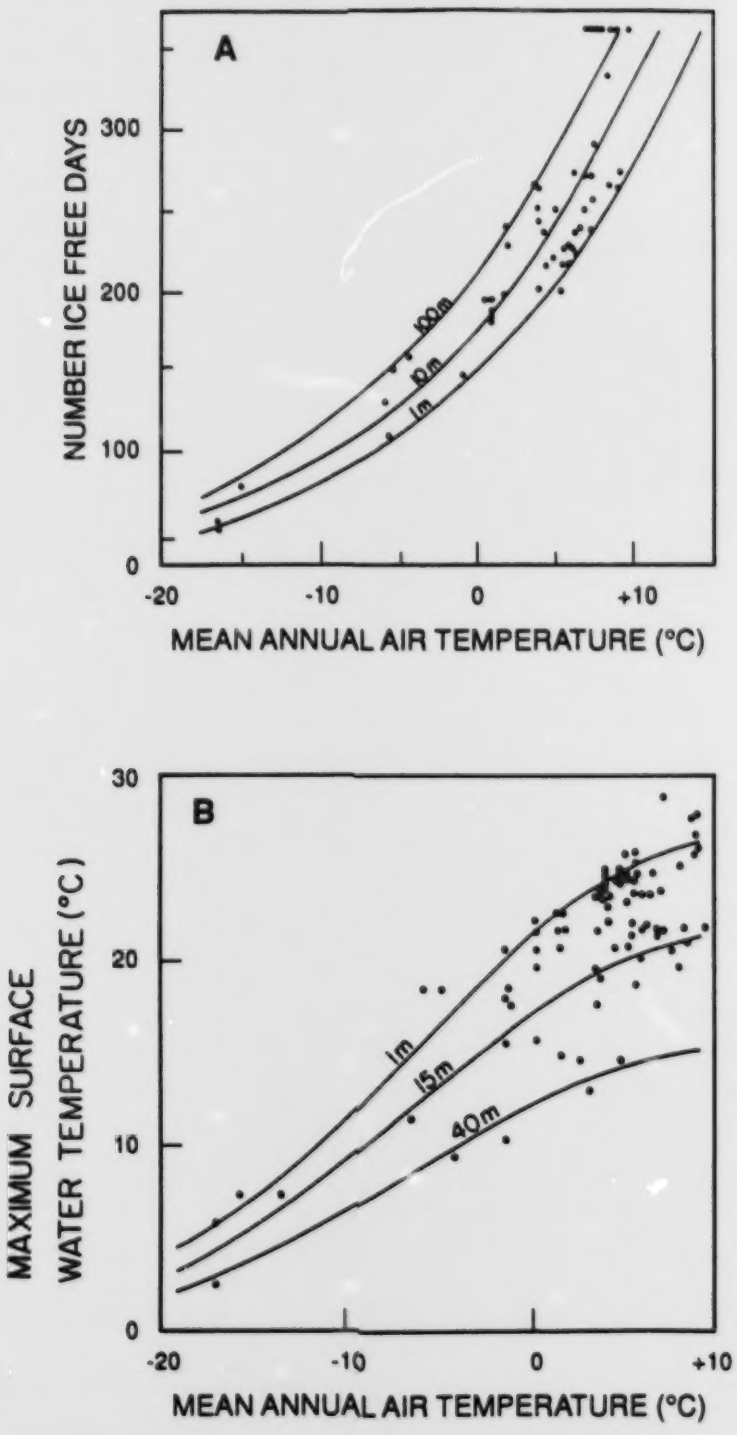

Figure 2.14. Relationships beteen mean annual air temperature and A. the number of ice free days, and B. the maximum surface water temperature in North American lakes. Separate curves show relationships for lakes of different mean depth. Redrawn from Shuter et al. (1983).

the ice-free season increased by three weeks. The documented increase in thermocline depth within the lake during this period effectively reduced the amount of available habitat for cold stenothermic organisms like lake trout and opossum shrimp.

A potential indirect consequence of climatic warming on freshwater habitats may stem from future requirements to construct and operate water-storage reservoirs, particularly in areas that are anticipated to become increasingly arid (Coutant 1981). Additionally, any interbasin water transfers that are undertaken in response to global warming effects, may create serious aquatic impacts.

Fish Thermal Physiology and Ecology

Fish are classified as ectothermic animals; they belong to the group of organisms whose major source of body heat is external. Since temperature profoundly affects the rates of physiological and ecological processes (Pauly 1980, Regier et al. 1990), fish are extremely sensitive to changes in environmental temperature. A voluminous literature documents the importance of temperature as an underlying environmental variable in aquatic environments. This section of the literature review summarizes several concepts developed by thermal physiologists, considers extensions of these concepts for fish ecology and fisheries production, and lastly, draws conclusions about the susceptibility of fish populations to climate-induced changes in their thermal environment.

Numerous studies have been conducted on the influence of temperature on physiological processes in fish (see for example, studies on sockeye salmon summarized by Brett 1971). The major means of body temperature regulation available to fish (and other ectotherms) is through behavioral mechanisms (reviewed in the Symposium on Thermoregulation in Ectotherms - Reynolds 1979). Additionally, there have been a number of studies which evaluate impacts of waste heat disposal on fish populations in aquatic environments (Richards et al. 1977, Houston 1982, Coutant 1987).

Houston (1982) reviewed temperature effects upon the toxicity of aquatic pollutants. For many heavy metals and organic pollutants, existing evidence is ambiguous or inconclusive with respect to temperature effects on the acute toxicity of these elements or compounds. Declines in toxicity, neutral effects, and increased toxicity with increasing temperature have been reported in studies of different heavy metals and organic pollutants. It would appear that temperature effects upon acute toxicity depend both on the fish species and pollutant involved, and generalizations are difficult.

Two concepts which characterize the response of aquatic animals to environmental temperature include *thermal tolerance* and *thermal preference*. Thermal tolerance

reflects the ability of aquatic organisms to tolerate temperature extremes, and is commonly measured by LT_{50} - the temperature which is tolerated by 50% of a test population for sustained periods in relation to prior thermal history and other influencing circumstances. A number of variables can influence thermal tolerance, including thermal history, seasonal and photoperiodic effects, geographical distribution, and ontogeny (Houston 1982). The concept of thermal preference is discussed by Reynolds (1977), who states that the single most meaningful characteristic of a species' thermal behavior is the "final preferendum", i.e., the temperature or narrow range of temperatures within which individuals will eventually congregate regardless of prior thermal experience. Thermal preference is usually measured in steep experimental temperature gradients or in some type of electronic shuttlebox (McCauley 1977) and is influenced by acclimation temperature, diurnal effects, seasonal adjustments and ontogeny (Houston 1982). In general, for both thermal tolerance and thermal preference, estimated values for juvenile stages are greater than those for adults. The observation that young fish select higher temperatures than do older conspecifics is consistent with distributions in nature, in which younger fish are often distributed in warmer, shallower waters than adults (McCauley and Huggins 1979).

Literature values of thermal tolerance and thermal preference for juvenile stages of the five species of Pacific salmon in the Fraser River watershed are the following (Brett 1952, Houston 1982):

	Thermal Tolerance LT_{50} (°C)	Final Thermal Preferenda (°C)
pink	21-24	11.7
chum	22-24	14.1
coho	23-25	11.4
sockeye	22-24	14.5
chinook	20-25	11.7

A number of studies have demonstrated that the preferred temperatures of fish often coincide with temperatures which optimize physiological function. For example, Brett (1971) has shown that the 15°C preferred temperature of juvenile sockeye salmon is also the temperature where active metabolic rate, metabolic scope, sustained swimming speed and growth rate are optimized. This correspondance in preferred temperature and physiological optimum temperature is clearly adaptive for sockeye salmon (Brett 1971). Although the thermal physiology of the other salmon species present in the Fraser River watershed (pink, chum, coho, and chinook) is not well-documented, they probably have a physiological optimum temperature within a few degrees of sockeye salmon (15° ± 2°C).

It is commonly observed that fish in nature are often found at lower temperatures than their final preferenda, as determined in the laboratory (Reynolds 1977). In sockeye salmon, physiological optimum temperatures for growth decrease as food ration decreases (Brett et al. 1969), reflecting temperature-related shifts in net food conversion efficiency under different ration levels. Discrepancies between final temperature preferenda and field distribution may also reflect the importance of other ecological factors which potentially override the importance of temperature as an environmental variable. For example, predation pressure from freshwater piscivores, e.g., northern squawfish, may strongly influence salmon behavior in freshwater and potentially override physiological selection pressures.

Independent of the role of temperature as a variable affecting physiological and ecological processes is its role as a proximate factor influencing fish distribution and orientation within aquatic habitats (Reynolds 1977). By analyzing fish distribution in a cold water temperature plume, Baltz et al. (1987) showed that temperature was an important variable influencing microhabitat choice by four fish species (rainbow trout, hardheads, Sacramento squawfish, and Sacramento suckers) in a California stream.

The concept of *thermal niche* has been applied in several studies to characterize fish responses to temperature. The *fundamental* thermal niche, as defined by Magnuson et al. (1979), is based on behavioral criteria, and includes the median temperature, plus or minus 33% of the laboratory determined thermal distribution (1 standard deviation) of fish in a temperature gradient. For most fish species, the width of the thermal niche is about ±2°C about the preferred temperature (Figure 2.15). While lethal temperatures set an ultimate bound on a thermal niche, they are usually so extreme as to have little influence on the fine tuning of an animal's resource utilization (Magnuson et al. 1979).

Magnuson et al. (1979) argue that animals will compete for and partition thermal resources in an analogous fashion as other consumable resources, e.g., food, and that temperature might be usefully considered as an ecological resource. Evidence from studies in Lake Michigan suggests that adult and young-of-the-year alewives *(Alosa pseudoharengus)* are spatially segregated across a thermal gradient (Brandt 1980), perhaps as a mechanism to reduce cannibalism. Other predominant fish species in Lake Michigan, including rainbow smelt *(Osmerus mordax)*, spottail shiner *(Notropis hudsonius)*, and trout-perch *(Percopsis omiscomaycus)* are also spatially segregated across the thermocline, despite rapid oscillations in thermocline position (Brandt et al. 1980). These findings have been interpreted as evidence for thermal niche partitioning, thus enhancing coexistence of fish species in Lake Michigan.

An interesting extension of the thermal niche concept has been recently undertaken by Christie and Regier (1988) to evaluate the influence of time-integrated measures of optimum lake habitat space (thermal habitat area) and volume (thermal habitat volume) as defined by the thermal niche. Significant relationships were obtained

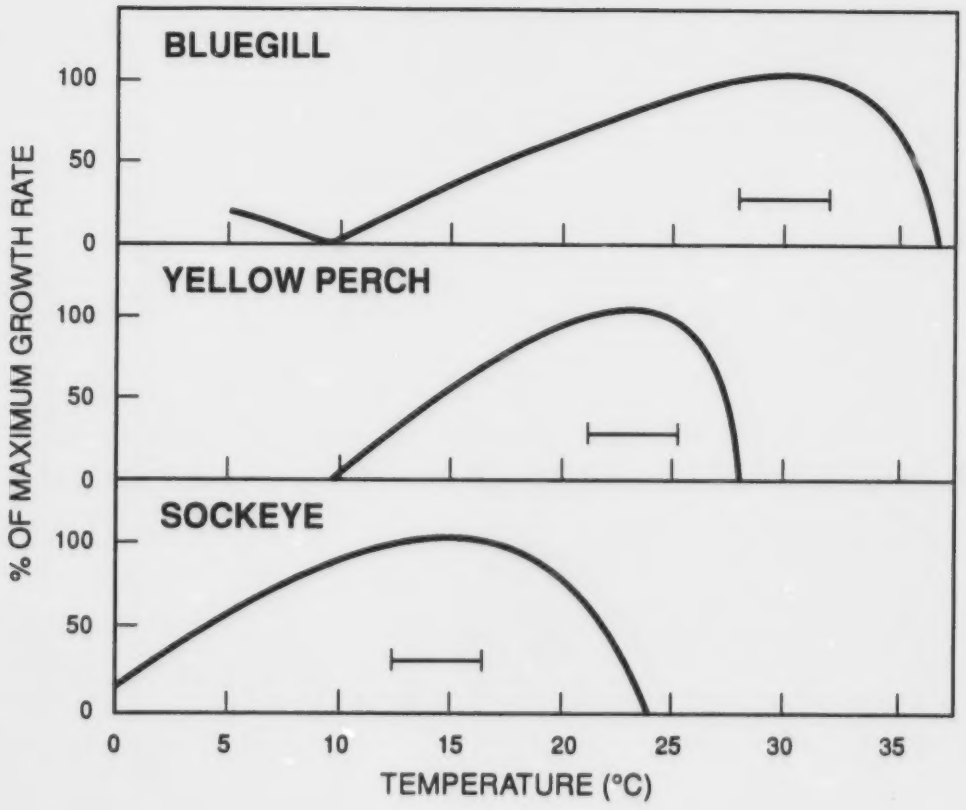

Figure 2.15. Relation between thermal niche (horizontal bar) and body growth with excess ration as a function of temperature for representative warm-, cool-, and cold-water fish. Redrawn from Magnuson et al. (1979).

between log-scaled measures of sustained yield and habitat quantity x seasonal duration within the fundamental thermal niche of four different commercial species (lake trout, lake whitefish, walleye, and northern pike) in 21 North American lakes (Figure 2.16). The results suggest that the availabilty of water within the temperature range which is physiologically optimal for a given species contributes strongly to the productive capacity of that species' population in a given lake.

Predation by freshwater piscivores is believed to exert an important structuring influence on fish communities in both lakes (Evans et al. 1987, Robinson and Tonn 1989) and streams (Brown and Moyle 1991). With higher aquatic temperatures, prey fish have more chances to have encounters with "hungry" predators (rather than satiated ones) because, other things being equal, predators need to consume higher numbers of prey in warmer water in order to satisfy their metabolic requirements (Pauly 1980). Thus piscivore-induced mortality rates could conceivably increase under higher temperature conditions. Empirical studies on northern squawfish *(Ptychocheilus oregonensis)*, an abundant predator of juvenile salmon in the Fraser River watershed, suggest that stomach evacuation rates are directly related to environmental temperature (Beyer et al. 1986). Thus higher aquatic temperatures might serve to increase salmon mortality rates through increased piscivore predation.

Based on the preceeding review, it is evident that global warming could potentially affect salmon populations in the Fraser River watershed in several ways. First, extreme high temperatures could conceivably cause mortality directly where salmon encounter high temperatures close to their limits of thermal tolerance. Secondly, global warming could potentially cause shifts in the thermal structure of aquatic habitats away from the thermal niche such that salmon physiological performance was compromised (e.g., growth rate). Thirdly, there are a number of indirect ecological changes with increased temperature (e.g., increased predation, increased susceptibility to parasites and pathogens, increased food abundance) that could profoundly affect salmon populations. Such ecological responses to climate warming are difficult to predict, and might be positive or negative from a fish production standpoint.

Effects of Global Warming on Fish

Several studies on future climate change impacts on fish populations and fish communities are reported in the proceedings of a workshop that was sponsored by the American Fisheries Society in September, 1988 (Regier et al. 1990). Together with other available reports, this section of the literature review summarizes known information on global warming effects with respect to fish habitats, distribution and community structure. Lastly, a set of studies pertaining to climate warming impacts on salmonids in the Pacific Northwest are reviewed and summarized.

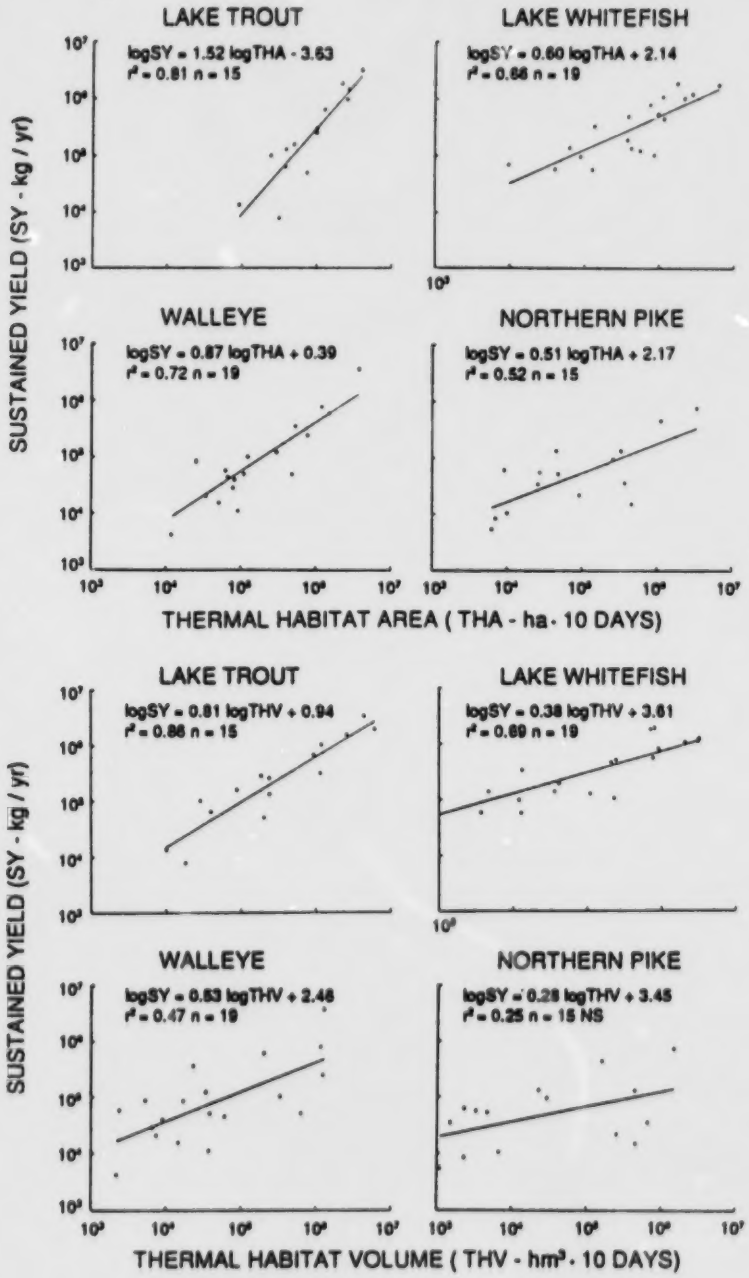
LAKE TROUT
logSY = 1.52 logTHA - 3.63
r² = 0.81 n = 15
LAKE WHITEFISH
logSY = 0.60 logTHA + 2.14
r² = 0.66 n = 19
WALLEYE
logSY = 0.87 logTHA + 0.39
r² = 0.72 n = 19
NORTHERN PIKE
logSY = 0.51 logTHA + 2.17
r² = 0.52 n = 15
SUSTAINED YIELD (SY - kg / yr)
THERMAL HABITAT AREA (THA - ha · 10 DAYS)
LAKE TROUT
logSY = 0.81 logTHV + 0.94
r² = 0.86 n = 15
LAKE WHITEFISH
logSY = 0.38 logTHV + 3.61
r² = 0.69 n = 19
WALLEYE
logSY = 0.53 logTHV + 2.46
r² = 0.47 n = 19
NORTHERN PIKE
logSY = 0.28 logTHV + 3.45
r² = 0.25 n = 15 NS
SUSTAINED YIELD (SY - kg / yr)
THERMAL HABITAT VOLUME (THV - hm³ · 10 DAYS)

Figure 2.16. Plots of total sustained fish yield versus A. thermal habitat area, and B. thermal habitat volume, in four freshwater fish species. Reproduced from Christie and Regier (1988).

Within freshwater fish habitats, anticipated climate warming effects on water temperature, water quantity and water quality, are summarized by Regier and Meisner (1990) who point out that in general, the size of stream fish populations should follow the changes in streamflow with climate change, since streamflow is a measure of habitat space. In one model for trout standing crop (Binns and Eiserman 1979), the effects of water temperature and water quantity act multiplicatively with respect to trout standing crop; it is therefore feasible that climate warming may increase salmonid populations in northern and high altitude temperate locations where extreme high temperatures are nonlimiting.

The impacts of climate warming on groundwater, and the role of groundwater in salmonid stream ecology, is reviewed by Meisner et al. (1988). These authors discuss physical processes controlling groundwater temperature, and predict that groundwater temperatures will follow the projected increases in mean annual temperature from climate warming. A general rule of thumb states that groundwater temperature can be approximated by adding 1°C to the local mean annual air temperature; within Canada, this might increase groundwater baseflow temperatures by 4-5°C following climate warming. Depending upon the ratio of baseflow to the average volume of stream flow during critical warm periods, this warming effect could strongly influence stream fish habitats in groundwater-dominated streams. Meisner et al. (1988) predict that in such streams at low altitudes and latitudes, optimal thermal habitats of salmonines will likely shrink in summer, and expand in groundwater-dominated streams at high altitudes and high latitudes.

Meisner (1990A) reported that for brook trout, whose upper incipient lethal temperature level is 25°C, there was a downstream summer thermal barrier at a temperature of 24°C in two Ontario streams. By applying GCM predictions, Meisner (1990A) calculated that elevated air and groundwater temperatures increased the maximum summer stream temperatures and moved thermal habitat barriers upstream in brook trout streams. This effectively reduced the summer thermal habitat by 42% and 30% in the two streams under consideration. Meisner concludes that stenothermic fish species (e.g., salmonids) may experience the greatest habitat effects of climate warming, and that such effects will likely become noticeable first in populations located at the margins of the species' geographic distribution.

Within the Great Lakes, the impact of climate warming on the optimal thermal habitat (defined by the thermal niche) and yield of fish within three thermal guilds (cold, cool, and warm) was analyzed by Magnuson et al. (1990). Following a simulated climate warming, thermal habitats increased for all fish species considered, with several rare exceptions. Habitats increased for all species in Lake Michigan, but only increased for cool- and warmwater fish in Lake Erie due to a hypolimnetic deoxygenation constraint on coldwater species. Limitations of the model results include the possible indirect influence of climate warming on fish habitats, for example, the influence on ice cover, water level, stream flow, nutrient input, and water quality through changes in

industrial development, agriculture, and forestry in the region.

Bioenergetics simulations by Hill and Magnuson (1990) suggest that annual growth rates of yearling fish (lake trout, yellow perch, largemouth bass) would increase with climate warming if prey consumption increased, but would decrease if prey consumption was constant. Changes were most pronounced during spring and autumn seasons, owing to a lengthening of the period during which behavioral regulation takes place. Where thermoregulation was constrained (e.g., due to a hypolimnetic oxygen depletion within Lake Erie), fish were predicted to experience decreased growth, or even weight loss, through the occupation of suboptimal temperatures. Global warming will likely increase epilimnetic temperatures within the Great Lakes (both the mean and the maximum). Hill and Magnuson (1990) predict that overall fish yields will likely increase following global warming, consistent with relationships reported by Schlesinger and Regier (1982), but that certain fisheries would likely collapse, depending on changes in prey abundance and the availability of oxygenated hypolimnetic water in warmer regions. The results show that food web dynamics and the potential for thermoregulation will greatly influence the direction and magnitude of changes in fish growth.

Global warming effects can potentially influence freshwater fish distribution on both small- (within lakes or streams) and large- (between lakes, streams, or watersheds) spatial scales. The small-scale influence reflects the importance of temperature as a proximate factor in fish orientation behavior and distribution (Reynolds 1977). The large-scale influence is especially pertinent for fish populations situated on the margins of their geographic distribution.

Meisner (1990B) showed that the minimum altitude of streams supporting brook trout is higher in the southern part of the range than in the north due to high summer temperatures in the low altitude streams of the south. In northern latitudes (Pennsylvania, New York, Ontario) where groundwater is cooler, brook trout are present at relatively low elevations (0-300m). Under a climate warming scenario, stream habitats along the southern margins of the brook trout distribution were predicted to become inhospitable for brook trout due to unsuitably high summer temperatures (Figure 2.17).

Under a future warmer climate, the converse effect of a range reduction by coldwater species is a range expansion of warmwater species. Shuter and Post (1990) describe the relevant physiological processes that limit the northern extension of warmwater species. Due to size-related physiological processes, small fish in wild populations tend to be less tolerant of winter starvation conditions than large fish. Population viability in northern fringe populations hinges on the ability of young-of-the-year fish to complete a minimum amount of growth during their first year of life. From south-to-north, this ability is increasingly restricted as the growing period shortens and the starvation period lengthens. Such a constraint is sufficient to explain the present

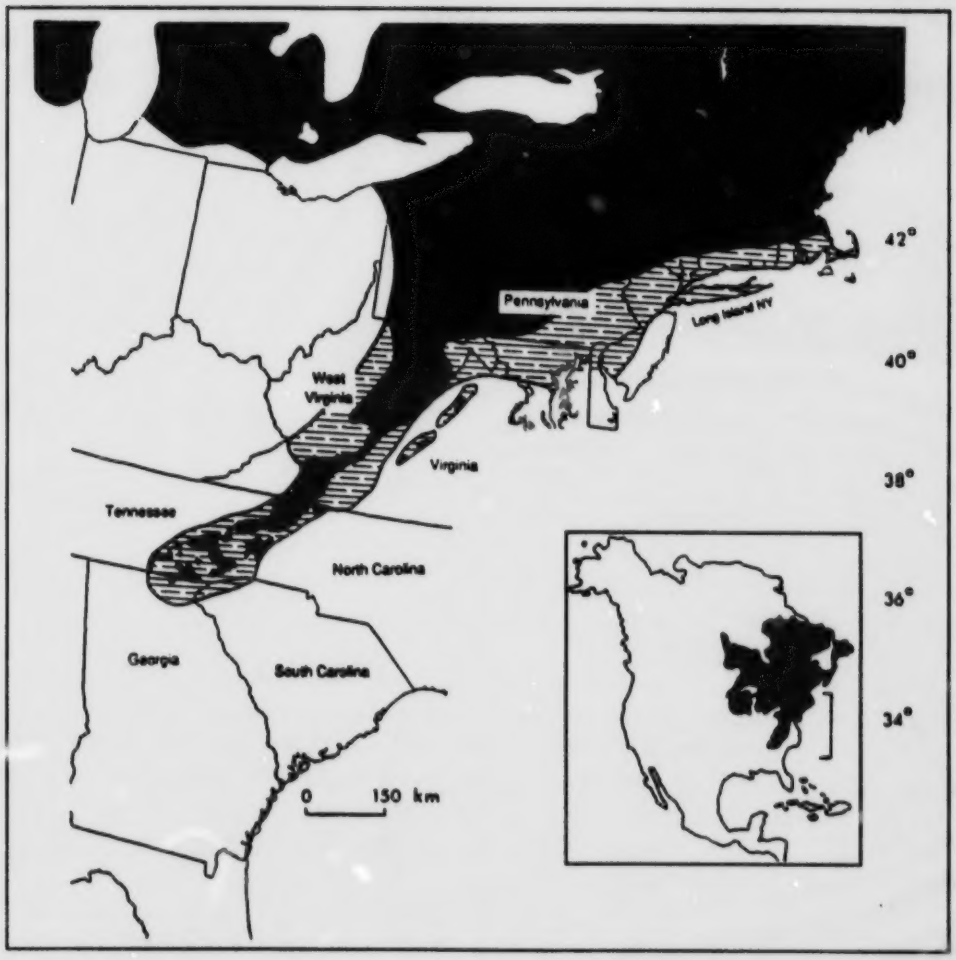

Figure 2.17. Present distribution of brook trout in the southern part of the native range in eastern North America (hatched and opaque areas). The present area that becomes unsuitable in a GCM climate warming scenario is indicated by the hatched area. Reproduced from Meisner (1990B).

northern limits of yellow perch in central and western North America, Eurasian perch in Eurasia, and smallmouth bass in central North America. With the future relaxation of this constraint due to climate warming, both yellow perch and smallmouth bass should thrive well to the north of their present distribution in North America (Shuter and Post 1990).

Geographical distribution patterns suggest that the northern distribution of a large number of freshwater fish species is governed by temperature. For example, Meisner et al. (1987) review published data to show that the northern limit of the native distribution of many Ontario fish is governed by the following mean July air temperatures:

Mean July air temperature		
21.0°C	18.0°C	16.7°C
spotted gar	northern brook lamprey	goldeye
lake chubsucker	silver lamprey	blacknose shiner
black redhorse	bowfin	spottail shiner
golden redhorse	creek chub	mimic shiner
gravel chub	rosyface shiner	fathead minnow
silver chub	bluntnose minnow	rock bass
brindled madtom	smallmouth bass	sauger
green sunfish	largemouth bass	lowa darter
eastern sand darter		river darter
greenside darter		
channel darter		
blackside darter		

It therefore seems likely that climate warming will promote the northern range expansion of a broad spectrum of freshwater fish. Within the Great Lakes region, Mandrak (1989) evaluated the probability of invasion by 58 common, widely distributed fish species from the Mississippi and Atlantic Coastal basins. Comparisons with the ecological characteristics of 11 recent invaders led Mandrak (1989) to the conclusion that 27 of the 58 species were potential invaders of the Great Lakes as a response to global warming.

By implication, if climate warming causes small- and large-scale shifts in freshwater fish distribution, then local shifts in fish community structure would seem highly likely. Such shifts are difficult to predict on an *a priori* basis, given the present status of understanding of fish community ecology and the potentially complex pathways through which climate can influence aquatic communities.

Tonn (1990) presents a useful conceptual framework for the analysis of fish community changes in response to future global warming. Within this framework, fish

assemblages can be viewed as products of a series of filters (continental, regional, lake-type, and local), operating at different spatial and temporal scales, through which a fish assemblage's component species must pass. Tonn (1990) points out that the most important large-scale effect of climate warming on freshwater ichthyofauna would be shifts in geographic distributions resulting from local extinctions of southerly populations, and invasions of species into areas further north than their current distributional limits. Tonn (1990) discusses the effects of different invader traits ("specialist" vs. "generalist") on the ability of fish to colonize freshwater habitats, and points out that: *"A region with a high proportion of specialists may be especially vulnerable to climate changes if those changes adversely alter environmental conditions, resources, or the isolation of habitats on which the species specialize".*

Analysis of the potential future climate warming impacts on Great Lakes fish species (Meisner et al. 1987) suggests that rather than the local extinction of specific fish taxa within the basin, community shifts and changes in relative abundance would be most probable. The habitat warming within streams and lakes would shrink populations of salmonines and coregonines (through reductions in preferred thermal habitat), and allow range expansions of cyprinids, esocids, centrarchids, and ictalurids. This would be coupled with invasions by exotics from the Mississippi and Atlantic Coastal drainages (Mandrak 1989). Many of the predicted alterations in fish community composition discussed by Meisner et al. (1987) are similar to community shifts associated with eutrophication processes (Larkin and Northcote 1969).

Chatters et al. (1991) provide a preliminary analysis of the potential impacts of climate warming on spring chinook salmon within the Yakima River subbasin of the Columbia River. The basic approach was to take mid-Holocene period (6,000 to 8,000 yr. B.P.) paleohydrology data (generated from floodplain sediment sequences and mussel shell growth patterns) when atmospheric temperatures were approximately 2°C higher than the present. The reconstructed hydrological record indicates that: 1) stream flows were less than 70% of modern; 2) many small, low elevation, perennial streams became intermittent (dry during part of the year); 3) streams had finer bed loads (greater sedimentation); 4) water temperatures were higher; and 5) the spring peak flow (freshet) ended three to four weeks earlier than it does today. Chatters et al. (1991) then altered the survival parameters for different life history stages in a tributary simulation model to reflect the impact of the altered (mid-Holocene) hydrological conditions on overall chinook salmon production. Many of the parameters were altered in an arbitrary but nevertheless realistic manner (e.g., tributary smolt capacities were reduced by 33% to reflect a 33% overall reduction in stream flows). Simulation results suggest that a 2°C climate warming could reduce overall Yakima sub-basin spring chinook salmon production by about 60% (from 9800 returning adult fish at present, to 3900 fish after climate warming). With climate warming, the potential future benefits of enhancement projects would be reduced by 49% (benefit/cost ratios were similarly reduced by 49%). The model was very sensitive to reductions in chinook smolt survival during outmigration - a 25% decrease in smolt

survival reduced adult production by 53%. This effect was probably the result of a shift in the timing of the spring freshet.

A comprehensive analysis of future climate change impacts on all of the major salmon and steelhead stocks of the Columbia River basin was undertaken by Neitzel et al. (1991). Many of these stocks warrant special attention since they are under high risk of extinction, including 36 out of 76 Columbia River basin stocks (Nehlsen et al. 1991). The study extended the analysis of Chatters et al. (1991) and similarly evaluated the effects of a climatic return to mid-Holocene conditions when Pacific Northwest temperatures averaged 1° to 2° warmer than the present. The analysis concentrated on the effects of four hydrological variables on salmon survival, including the duration of peak flow, sedimentation, temperature, and annual flow. The authors first generated a qualitative set of postulated impacts (positive, negative, or neutral) from climate warming on the different sub-basins of the Columbia, according to specific criteria (Table 2 in Neitzel et al. 1991). Next, the postulated effect of climate warming on the various salmon species (or runs) within different Columbia River sub-basins was rated according to a 5-scale evaluation criteria (Table 4 in Neitzel et al. 1991): 1-severe adverse environmental change resulting in possible extinction of salmon stock; 2-adverse environmental change resulting in possible reduction of salmonid production; 3-no impact to the environment and no change in salmonid production; 4-environmental improvement resulting in possible increase of salmonid production; 5-environmental conditions maximized for salmonid production. Lastly, the current status and overall impact of climate change on specific Columbia basin salmon stocks was summarized in tabular format (Table 5 in Neitzel et al. 1991).

Different species and runs of salmon within the Columbia River sub-basins were differentially vulnerable to climate change impacts (Neitzel et al. 1991). The mid-Holocene climate scenario had mostly negative effects on spring and summer chinook due to unfavourable effects on both the timing and size of the spring freshet. This influence was rated more significant than the impacts from altered precipitation levels. Impacts on fall chinook and coho were dependent upon water flows and temperatures, as well as freshet timing. Overall effects on these latter species depended upon their location within the Columbia River basin and were largely positive in west side rivers, and largely negative in the more easterly streams. Sockeye (already severely depressed within the Columbia basin) were negatively affected by climate change impacts due to warmer summer lake temperatures, and reduced spring flows. Lastly, since steelhead tolerate warm water and intermittent stream environments, they were predicted to be largely unaffected, or even enhanced by a warmer climate.

These results suggest that climate warming impacts will likely be species- and stock-specific within the Columbia River, depending upon the stock location within the basin. The magnitude and direction of climate change impact appears to depend upon whether annual precipitation would increase, decrease, or shift seasonally; regional

predictions concerning precipitation changes following climate warming are not available at present. While somewhat subjective and based primarily on expert opinion, the analysis by Neitzel et al. (1991) provides explicit predictions concerning climate warming impacts on Columbia basin salmonids, and serves as a useful planning document upon which to base future enhancement, management, and conservation programs. The conclusion of the report recognizes that changed priorities in allocation of the region's water supplies (due to direct climate change impacts on the Columbia basin water resource) to competing water users (e.g., hydropower and irrigation interests) may exert a greater impact on salmon and steelhead than climate change itself. This conclusion emphasizes the need for integrated resource management planning on both a watershed and regional basis that embraces the possibility of significant climate change in the near future.

Impacts of future climate change have major implications for British Columbia's freshwater fisheries resource. A preliminary evaluation was undertaken by Northcote (1992) who identified the possible freshwater fisheries consequences of climate change in B.C. as follows:

Climate change impacts on:	Major concern:
migration	salmon stocks which presently experience high levels of prespawning mortality
spawning	early-fall spawners
development timing and emergence	premature emergence, reduced egg survival
feeding, growth, survival	reduced survival associated with oxygen depletion, increased frequency of "summer kill" events
distribution and community structure	altered fish distribution, invasions by exotics
fisheries management	greater variability and unpredictability

Due to their respective life histories and provincial distributions, Northcote (1992) concluded that cutthroat trout, pink salmon, and chum salmon should be less affected by climatic change, than should rainbow trout, Dolly Varden, lake char, coho, sockeye and chinook salmon.

The possible impacts of climate warming on Adams River sockeye salmon production were recently evaluated by Henderson et al. (1992). Climate warming impacts on two different life history stages were analyzed: juvenile sockeye salmon in Shuswap Lake, and adult sockeye salmon spawning in the Adams River. Higher temperatures and altered hydrological conditions were projected to reduce overall sockeye production within the nursery lake through several different limnological and biological pathways. Reduced growth of juvenile sockeye, associated with alterations in feeding conditions (zooplankton species composition) and the uncoupling of the sockeye thermal niche from the feeding niche was predicted to reduce sockeye growth rate in Shuswap Lake, thereby reducing overall marine survival rate (sockeye marine survival rate is size-dependent). No effects were anticipated on the Adams Rver adult sockeye prespawning mortality rate since the population is a late-run stock and there is no existing relationship between prespawning mortality and average October water temperature.

Fisheries Policy Options

With the recent scientific and public awareness of the potential magnitude and severity of global warming impacts on ecological, economic and social systems, a number of measures have been proposed to prevent, mitigate or adapt to altered climatic conditions of the future. On a global scale, loading of carbon to the atmosphere is increasing, and there has been little progress made towards stabilizing the emissions responsible for the enhanced greenhouse effect. Management of the global atmosphere is an important policy issue for all levels of government. This section of the literature review summarizes fisheries policy issues related to global warming.

Due to the omission of environmental variables in most fishery management models (e.g., stock recruitment models), Frye (1983) argues that current fisheries management is based on erroneous concepts of fisheries dynamics which could lead to disastrous misassessment of the ability of a stock to withstand fishing pressure under changing climatic conditions (for a contrasting view, see Walters and Collie 1988). Francis and Sibley (1991) show how fisheries production in marine environments may be linked to the action of low frequency climatic events which operate over large spatial scales on a time scale of decades or more. The impact of climate on marine fish population dynamics is thought to occur via direct and indirect influences on larval and juvenile fish survival, life history stages where the highest mortality occurs.

Francis (1990) predicts that fisheries management in the 21st century will have less to do with extractive conservation, and more to do with protection of regional and global environments. This prediction seems realistic, in view of the importance of regional biodiversity issues, particularly with respect to Pacific salmon (Nehlsen et al.

1991). Because of climate change effects, maintenance of regional biodiversity and discrete genetic stocks is made more difficult (Neitzel et al. 1991) and may imply that we have to (reluctantly) accept regional extinctions. Climate change also implies that we expend much more effort to preserve and restore stocks under threat of local extinction.

Frye (1983) describes several aspects of the fisheries policy dilemna associated with climatic change. He argues that by focussing on the climatic effects of doubling atmospheric CO_2, the misleading impression is given that CO_2 and climate change will not become a policy issue until the atmospheric concentration doubles in 50 years or so. He emphasizes that the CO_2 policy issue is current, continuing, and increasingly urgent. Due to the inherent lag time between atmospheric emissions and climatic effects (on the order of decades because of the slow ocean mixing processes), climatic change is essentially irreversible. Due to this time lag, policies may have to be formulated and maintained for decades without supporting data feedback, thereby reducing the ability of policy makers to eliminate uncertainties concerning a policy's effectiveness, necessity, or even its desirability.

Gucinski et al. (1991) discuss several philosophical questions that underlie the fishery policy issue associated with global climate change. Until recently, there has been a general willingness to assure present prosperity at the expense of future generations, and it is unclear how this ideal will influence decisions on climate change, or whether societal values will change. The issue relates to the cost of present investments to reduce negative impacts against the uncertain gain of future atmospheric protection. Gucinski et al. (1991) summarize the available policy options, and their associated assumptions as follows:

Option	Assumptions
1. Do nothing.	Predicted change is improbable, will have no measurable negative impacts, or the market will allow adjustments through pricing; compared to other problems facing humanity, climate change is less important.
2. Confine activity to research on global climate change.	There may be changes, but unless we have greater reliability in predicting change, taking action is premature and a delay in preventative or adaptative decisions is not critical.
3. Confine activity to research on climate change and its predicted effects.	A course of action is best decided on the basis of knowing probable effects; there is time for such analysis.

Option	Assumptions
4. Take mitigating steps that achieve some reduction in greenhouse gas emissions at low cost.	While not certain, climate impacts could affect food supplies, shorelines, and our "way of life". Action that is economically feasible could avoid a serious drain on resources later.
5. Mobilize an international effort to cut greenhouse gas emissions, protect fish stocks aggressively, breed hardy stocks, and expand aquaculture now.	The global scale of the problem merits priority over other social issues, or this issue links and amplifies problems such as population growth, food supply, war, disease, and cultural and economic decline.

It may be feasible to analyze the way society responded to adverse changes in fisheries production historically, and gain insights into how society might cope with regional climate change impacts on fisheries resources. Because the existing GCMs do not provide sufficient spatial resolution, and are in disagreement concerning precipitation changes, a "forecasting by analogy" approach was recently undertaken to evaluate societal responses to major fishery adjustments (Glantz 1990; Glantz and Feingold 1990). The approach required analysis of 15 different fisheries case studies from around the world. Several of the important conclusions from this analysis include: 1) Climate change will likely have an uneven impact on the marine environment; as a result, some commercially exploited populations will decrease and collapse in response to biological changes, while others might expand and prosper in response to those same changes; 2) International fisheries managers must be prepared to take objective decisions based on scientific information at hand and not on political expediency; to wait for researchers to reduce scientific uncertainty could jeopardize the long-term viability of a fishery; 3) The importance of the local (and sectoral) nature of the societal impacts underscores the need to educate relevant decision makers in those localities (and sectors) about the potential effects of a climate change on their normal way of "doing business"; and 4) Proactive (as opposed to reactive) adaptation and flexibility in the exploitation of marine resources are keys to ecological and economic viability.

The relevant fishery policy options for responding to global climate change (prevention, mitigation, adaptation) are discussed by Healey (1990). Prevention does not appear feasible because of difficult political, technical, and social constraints. Mitigation is an unattractive management response over the medium-to-long term for technical reasons and a high risk of failure due to unforeseen complications (e.g., hatchery impacts on wild salmon stocks). In the long term, adaptation is likely to be the most viable option. Healey advocates experimental "probing" strategies on small geographic scales so that the inevitable management mistakes are not devastating.

Such a strategy could potentially increase agency responsiveness to new fish production opportunities that result from global climate change.

Fleagle (1991) evaluated the policy implications of global warming for the Pacific Northwest based on recent GCM predictions. The following figures show the average of three GCM projections (Canadian Climate Centre, Geophysical Fluid Dynamics Laboratory, and United Kingdom Meteorological Office) associated with a future doubling of CO_2 concentration, in the Pacific Northwest (N. Cal.,Oregon, Wash., W. Brit. Col.) reported by the recent (1990) Intergovernmental Panel on Climate Change Working Group:

	Change in temperature (°C)	Change in precipitation (mm/day)	Change in soil moisture (cm)
Winter	+3.8	+1.3	+1.7
Summer	+4	-0.7	-2.3

There was agreement among all three GCMs in the direction of change, and each model projected significant warming in winter and summer, *increases* in precipitation and soil moisture during the winter, and *decreases* during the summer by significant amounts. Changes in river flow and water storage were projected for the Pacific Northwest. As an example, for the Columbia River region upstream of the Dalles Dam, 3°C winter warming would imply a 500m upward displacement of the snowline, reducing the snowpack area by 44% (from 72% to 41% of the watershed). A winter warming of 6°C would result in a 1000m upward displacement of the snowline, reducing the snowpack area to 13% of the watershed, a reduction of 82%. In response, winter runoff would be likely to increase substantially, and river levels would be expected to peak much earlier in the spring than at present. Summer runoff would be reduced substantially below present levels. Due to these global warming effects on Northwest water resources, Fleagle (1991) anticipates vigorous future policy debate about whether to add reservoir capacity in the Columbia River watershed. Out of the three resource sectors considered (forests, agriculture, and fisheries) analysis of climate change effects on anadromous fisheries was considered the most complex (Fleagle 1991).

Fleagle (1991) emphasizes that most important societal decisions are based on uncertain knowledge, and that this will be the case for global warming policies in the Pacific Northwest. He also challenges the inhabitants of the Northwest to take a bold, new role in environmental leadership: *"The legislatures and executives of the states and provinces should jointly draw up and adopt a resolution establishing the goal of making the Northwest a model for responsible and farsighted environmental practices, including actions to mitigate the adverse effects of possible climate change."*

3. Prediction of Freshwater Habitat Changes

Based on the information summarized in the literature review, the prospect of global warming in the Fraser River watershed is highly probable in the near future, and the future impacts on salmon habitat and salmon populations will be substantial. Overall climatic conditions in the Fraser basin by the middle of the 21st century will be similar to current conditions that occur further south. Phillips (1990) predicts that by the year 2030, enhanced greenhouse warming will give Vancouver the 1980s climate of San Francisco. Both the warming effect and the future alterations in precipitation patterns will greatly influence the regional hydrology within B.C. This section of the report summarizes the projected climatic changes for the Fraser River watershed, and derives some preliminary predictions of climate warming impacts on freshwater fish habitats.

There is considerable regional variation in the climate of B.C. (Chilton 1981). As depicted in Figures 3.1 and 3.2, there are three different climatic and hydrologic regions within the Fraser River watershed, including the Coast Mountains, the Interior Plateau, and the Eastern Mountains. There is approximately an order of magnitude difference in the amount of annual precipitation throughout the watershed (Figure 3.3), and this variation, together with differences in seasonal timing of precipitation, snowpack storage and glacier melt imply differences in water storage capacity and runoff pattern for the different sub-basins in the Fraser River (Moore 1991). Climate change will most likely affect the three hydrologic regions of the Fraser River watershed in different ways that are not presently easy to predict.

McBean (1991) discusses some of the difficulties in obtaining regional climate change predictions for B.C., including: 1) GCMs were not designed to produce regional climate scenarios; 2) the B.C. climate is greatly influenced by mountains which are only qualitatively represented by GCMs; and 3) the GCMs are deficient in their representation of the oceans which are an important controlling feature of the B.C. climate. Bearing in mind these qualifiers for B.C., under a doubled CO_2 scenario the GCMs predict an equilibrium winter warming of 7°C and an equilibrium summer warming of 4°C. Both of these estimates have an uncertainty of 3°C, and coastal areas will likely warm by 1-2°C less during both summer and winter due to the marine influence on coastal climate. McBean (1991) points out that these estimates should be scaled downwards to account for a warming lag induced by the ocean, and gives the following temporal estimates (°C) for warming increases in B.C.:

year	scaling	winter	summer
2000	0.16	1.0	0.5
2025	0.37	2.5	1.5
2050	0.60	4.0	2.5

During winter, equilibrium precipitation changes will be around 0.5 mm d^{-1} in the interior, and around 1 mm d^{-1} along the coast. During summer, precipitation increases

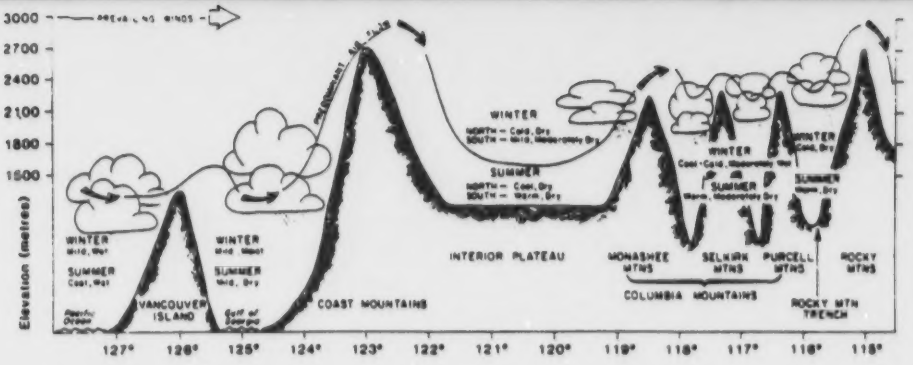

Figure 3.1. Latitudinal cross section of southern British Columbia. Reproduced from Chilton (1981).

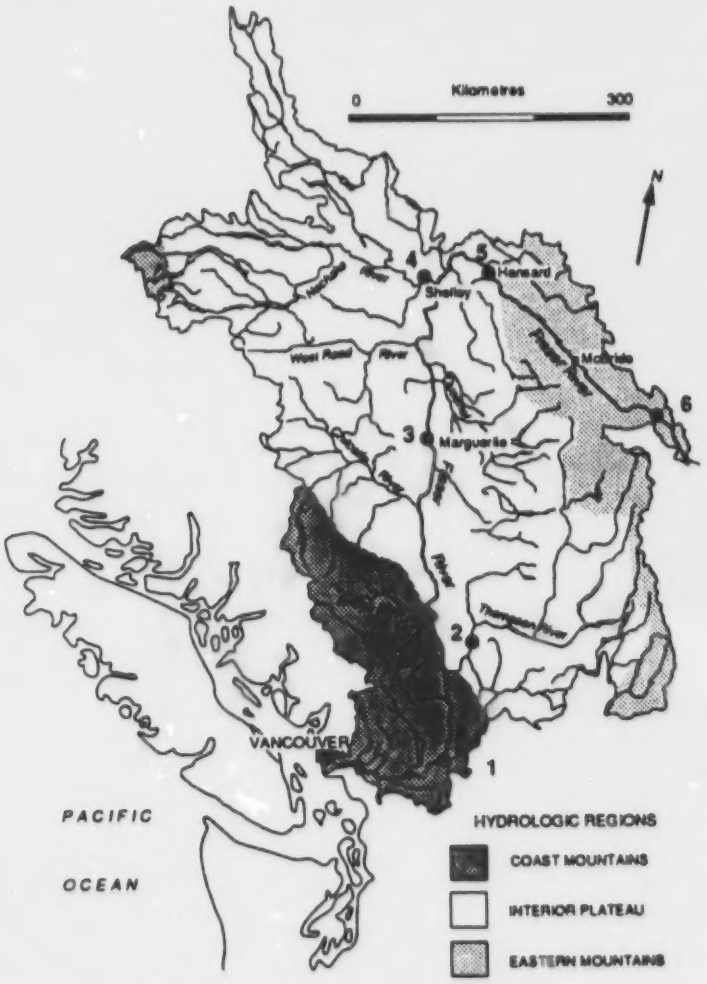

Figure 3.2. Hydrologic regions in the Fraser River basin. Numbers refer to major hydrometric stations. Reproduced from Moore (1991).

Figure 3.3. Mean annual precipitation (mm) in the Fraser River basin. Reproduced from Moore (1991).

will be smaller, and could be negative (i.e., decreased precipitation) particularly in the interior of the province.

These predictions imply that the streams, rivers and lakes within the Fraser River watershed will show future alterations in temperature and flow conditions related to future atmospheric warming and alterations in precipitation conditions. McBean and Thomas (1991) comment that: *"The socioeconomic impacts of changes in precipitation may well be larger than impacts of a warmer climate. In many respects, the most important weather element in terms of its impact on ecosystems and human activities is precipitation.....Of concern are the small* (summer) *decreases over most of Southern British Columbia, Washington, and Oregon, in particular the decreases of 10mm/month over eastern Washington and the interior of British Columbia. These already dry regions could have significantly worse water availability problems with reduced precipitation and increased evaporation."*

Many of the predicted alterations to precipitation with global warming appear to have already commenced. Danard and Murty (1988) compared the mean annual precipitation conditions in B.C. for the periods 1931-1960, and 1951-1980, and detected positive changes in mean annual conditions along the coast (up to 30cm), and negative conditions in the interior (decreasing as much as 11cm).

The consequences of climate change on the hydrology of B.C. are discussed by Coulson (1989) and Slaymaker (1990, 1991). Slaymaker (1990) summarizes data which show that runoff changes in B.C. rivers over the period 1913-77, including the Fraser River, were broadly controlled by precipitation changes. This observation is consistent with the point made by Coulson (1989) that streamflow integrates the climatic effects of precipitation and temperature over a watershed. The influence of climate on regional hydrology and the possible effect of climate change is illustrated by Coulson (1989) with an example from the Okanagan watershed. Within this watershed, the following estimates show what might happen to runoff if global warming increases evapotranspiration by 10%, and decreases basin precipitation by a modest 10%:

	Present (mm)	With climate change (mm)
Precipitation	675	610
Evaporation	600	660
Runoff	75	-50

Within the Okanagan basin, Okanagan Lake is considered to be the "master lake" due to its large volume and long water retention time (Stockner and Northcote 1974). Under the global warming scenario (above), Okanagan Lake would lose more water to evaporation than would enter from its tributaries (Coulson 1989). Although the magnitude of change under this scenario is somewhat speculative, the implications

for aquatic resources and water resource management in the Okanagan basin are serious.

In spite of the potential severity of global warming impacts on the hydrology of B.C. watersheds, the possible regional effects are not well understood. This is reflected in the recent statements by hydrologists, including Slaymaker (1991):

> *"We do not know what the impact of climate change on British Columbia's hydrology will be. Given the wide range of potential impacts on fish, forestry, water supply and land use, it is urgent that focussed research on B.C.'s water balance at regional scale be implemented."*

and Coulson (1989):

> *"It is not that we just don't know the magnitude of the change on the water resource - we don't even know the direction the change will take."*

Without good information on the regional hydrological impacts of climate change, the practicality of deriving useful climate warming predictions on aquatic organisms is considerably diminished.

A review of the hydrology of the Fraser River was recently undertaken by Moore (1991). In most of the sub-basins within the watershed, the seasonal hydrographs reflect the melting of seasonal snow accumulation, with the bulk of the runoff occurring in spring and summer, and with low flows in winter when most of the precipitation falls as snow and is stored in the snowpack. The prolonged seasonal melting of snow and ice in the watershed is reflected in the June peak ("spring freshet") of the seasonal hydrograph measured at Hope. An exception to this seasonal pattern occurs in low elevation coastal basins of the watershed (e.g., the Salmon River drainage near Langley) which are dominated by autumn-winter rainfall, with high winter flows and low summer flows when rainfall is low and evaporation losses are great.

Moore (1991) compared the climatic conditions at four measuring stations within the Fraser River watershed (Agassiz, Fort St. James, Salmon Arm, and Wistaria) with a long (60-100 years) time series of observations. While overall precipitation was approximately constant, there was a consistent decline in snowfall at all four stations from about the mid-1970s onwards. Consistent with this observation was an apparent warming trend at all four stations from about 1970 on. At approximately the same time, streams upstream of Hope began to show declines in flow which are reflected in the deviations in the mean annual flow measured at Hope (Figure 3.4). The flow changes are probably related to the observed post-1970 reduction in snowpack, by virtue of a relationship between snowpack and Fraser River discharge (Figure 3.5). Many of the recent changes in Fraser basin climatology and hydrology discussed

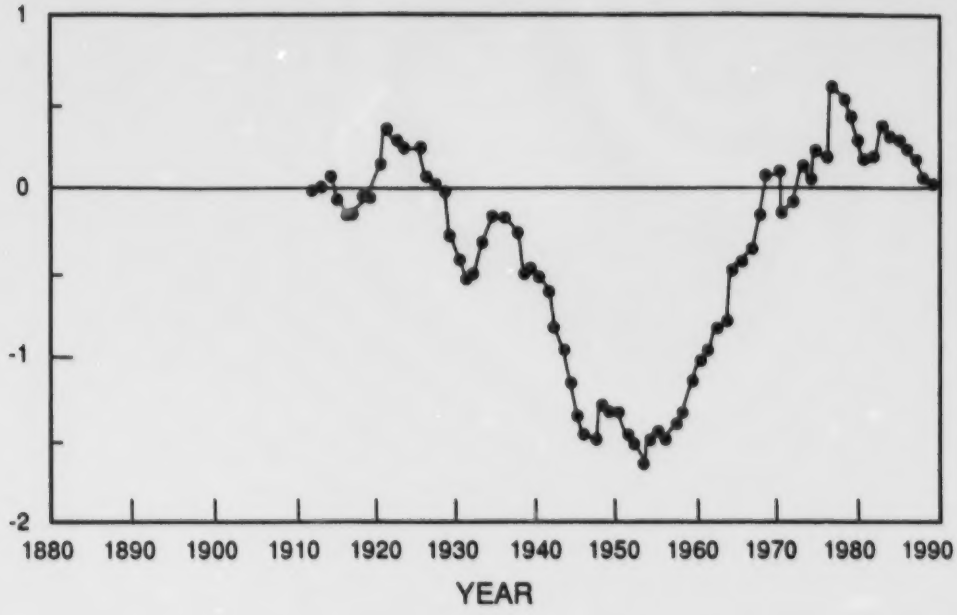

Figure 3.4. Plot of adjusted cumulative deviations from the mean flow of the Fraser River at Hope. Reproduced from Moore (1991).

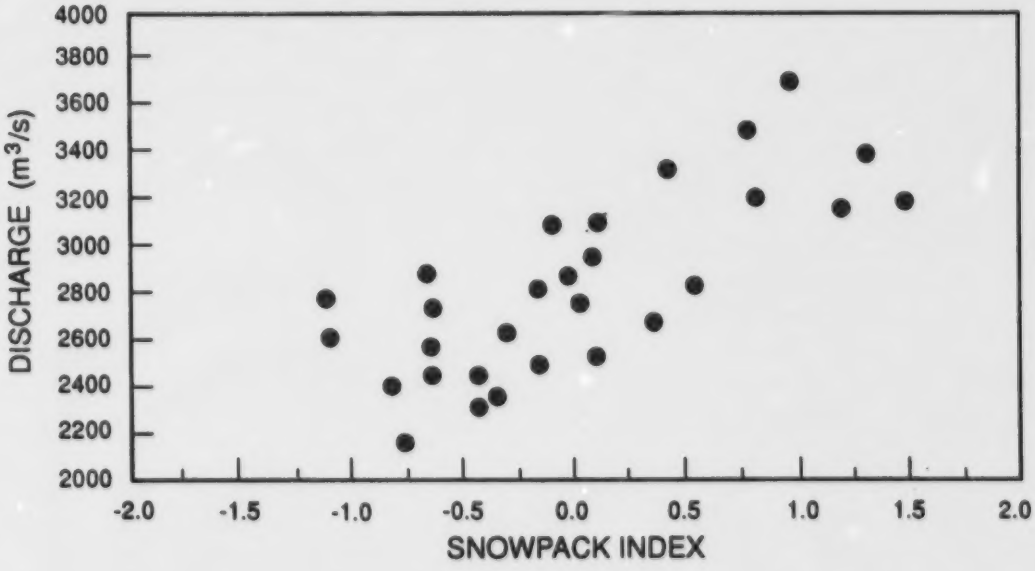

Figure 3.5. Mean annual flow of the Fraser River at Hope versus an aggregate index of peak snow accumulation. Reproduced from Moore (1991).

by Moore (1991) were independently documented by Danard and Galbraith (1988), adding credibility to their significance.

Moore (1991) concluded that by producing changes in snow accumulation in the Fraser River watershed, climatic forcing was the most probable cause for the observed shifts in mean Fraser River flow (as opposed to other influences, e.g., changes in watershed cover). The latter conclusion was further substantiated by analyses which showed that both Fraser River flows and snowpack accumulation were negatively related to the mean Northern Hemisphere temperature conditions. By comparing flow conditions during a warm period (1938-1947) with those during a cold period (1963-1972), Moore (1991) showed that for the Fraser River, both maximum and minimum flows were higher during the cold decade. The timing of minimum flows was about the same for both decades, but maximum flows occured earlier during the warmer decade. These analyses imply that both snow accumulation and Fraser River flow will diminish following future greenhouse-induced global warming. Moore (1991) also suggests that the seasonal timing of Fraser River runoff might change following global warming. If winter storm freezing levels are higher in a warmer climate, more precipitation will likely fall as rain and runoff, rather than be stored as snowpack. These predictions are qualitatively similar to those derived by Lettenmaier and Gan (1990) for the Sacramento-San Joaquin River basin.

Future streamflow scenarios based on GCM outputs were qualitatively different from those suggested by the empirical analysis described above. Two different GCM scenarios predicted overall increases in the Fraser River runoff at Hope associated with increased precipitation in mountain regions (Moore 1991). This latter result was obtained even when Interior Plateau runoff was decreased by 50% to simulate reductions in precipitation, suggesting that Fraser River flows at Hope were more sensitive to changes in runoff from the mountain regions than to runoff changes from the Interior Plateau. Moore (1991) concludes that the lack of agreement between the empirical analysis and the GCM water balance approach emphasizes the uncertainties in making predictions of regional hydrological responses to global warming.

In summary, the following are the anticipated changes which may occur in freshwater habitats of the Fraser River following global warming:

Streamflows - it is likely that there will be higher winter runoffs. This is due to a reduction in the amount of precipitation falling as snow, and an increase in winter precipitation levels, particularly in the Coastal Mountain portion of the watershed. Winter streamflow increases and flooding will be most severe in the Lower Fraser, Lillooet, and Bridge-Seton watersheds. It is likely that summer runoffs will be reduced throughout the entire Fraser, and particularly in the Interior Plateau region, including the North Thompson, South Thompson, and Thompson-Nicola watersheds. The overall timing of the spring freshet of the Fraser will probably occur several weeks earlier than it does at present.

Thermal characteristics - average stream and groundwater temperatures in the Fraser watershed will increase and generally follow the future alterations in atmospheric temperature. As well, due to an interaction between temperature and flow, reduced summer flows will contribute to higher stream temperatures. This is related to a lower future snowpack and reduced summer discharges which will create higher peak and average stream temperatures (independent of the atmospheric temperature effect). Similarly, stream temperatures may increase if extraction requirements intensify, since a smaller water volume will warm more efficiently than a larger volume. Stream temperature increases will be most extreme during spring, summer and fall periods, and the duration of winter periods of cold water temperature ($< 4°C$) will be reduced. Within Fraser watershed lakes, temperatures in surface waters and epilimnetic regions will also increase, however the overall lake heat budgets may be influenced more by alterations in prevailing wind patterns which are presently difficult to predict.

4. Identification of Vulnerable Species

The Fraser River produces more Pacific salmon than any other single river system in the world (Northcote and Larkin 1989) and supports a large number of discrete salmon stocks within the sub-basins of its watershed. The Fraser River ESD Task Force is presently developing site-specific habitat and stock management plans for the different sub-basins of the watershed (Figure 4.1). It is anticipated that this effort will provide a detailed inventory of salmon stock distribution throughout the watershed which will define the present status of the resource and its potential productivity over the long term. For the purposes of the present analysis, this section of the report reviews both the freshwater life history and spawner distribution of the respective salmon species throughout the watershed. Based on these two parameters and an evaluation of anticipated future freshwater habitat changes (Section 3), initial conclusions are derived concerning the relative vulnerability of different species of Fraser River salmon to climate warming effects.

Table 4.1. Number of streams, rivers, and lakes, where spawning salmon have been recorded in Fraser River sub-basins. Reproduced from Birtwell et al. (1988).

Sub-basin	Pink	Chum	Coho	Chinook	Sockeye
Stuart	0	0	0	9	39
Upper Fraser	0	0	0	16	1
Nechako	0	0	0	6	8
West Road	0	0	0	1	0
Quesnel	1	0	2	3	4
Chilcotin	0	0	0	4	4
North Thompson	0	0	27	14	7
Thompson	4	0	6	7	1
South Thompson	3	0	28	11	16
Bridge	2	0	2	2	2
Middle Fraser	13	3	11	7	9
Lillooet	9	17	32	11	22
Lower Fraser	40	58	75	7	11
TOTALS	72	78	183	98	124

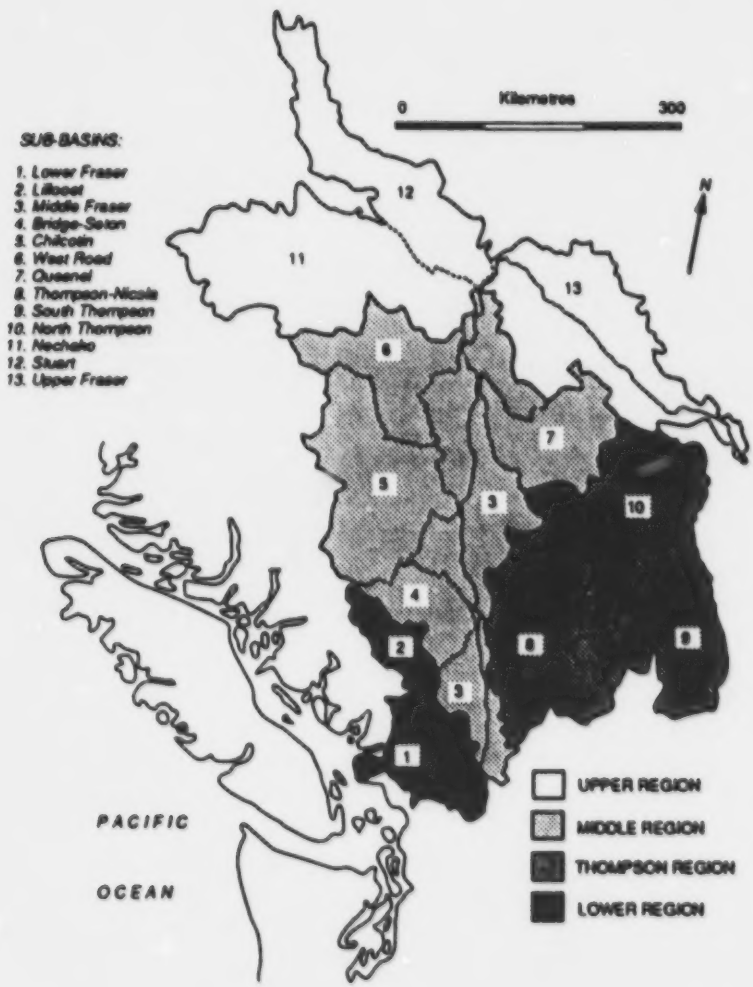

Figure 4.1. The four major regions of the Fraser River watershed, and their respective 13 sub-basins. Reproduced from Northcote and Burwash (1991).

A preliminary inventory of salmon stock distribution within the Fraser watershed is shown in Table 4.1 and Figure 4.2. A quantitative regional analysis, comparing average annual spawning escapements to the sub-basins of the Fraser watershed over the period 1951-1989, was undertaken by Northcote and Burwash (1991) and is shown in Figure 4.3.

Both pink and chum salmon spawning areas are concentrated in the lower reaches of the Fraser, particularly in the Lower Fraser and Lillooet sub-basins. Substantial numbers of pinks, and significant numbers of chum salmon spawn within the Fraser mainstem below Hope. Significant numbers of pink salmon also spawn in areas of the Thompson-Nicola and Bridge-Seton sub-basins. Juvenile pink and chum salmon spend only a restricted period in freshwater prior to migrating into the Fraser estuary and Georgia Strait; a recent pink fry marking experiment suggested an average migration time of only 27 hours for pink fry to descend from the Seton River to Mission in the Fraser River mainstem below Hope (R.Lauzier, DFO, pers. commun.).

When compared to salmon with protracted juvenile residency in freshwater (coho, sockeye, and chinook), Fraser River pink and chum salmon may be relatively invulnerable to freshwater effects of global warming[1]. Northcote (1992) evaluated the relative susceptability of different freshwater salmonids in B.C. to global warming effects and concluded that cutthroat trout, pink and chum salmon would be less vulnerable to such effects than rainbow trout, Dolly Varden and lake char, or coho, sockeye and chinook salmon. This is because the distribution of the former three species corresponds closely to the Pacific Cordilleran ecoclimatic province (Figure 4.4), which is predicted to show little change in area, and probably the least change in climate following a future doubling of CO_2 concentration (over pre-industrial levels).

Coho salmon in the Fraser River spawn primarily in the tributaries of the Thompson River and the Lower Fraser and Lillooet sub-basins (Table 4.1; Figure 4.5). The Lower Fraser sub-basin accounts for approximately 75% of the Fraser River coho salmon production (Henderson 1991), which inclusively is the largest single producer of coho salmon in British Columbia. Juvenile coho in the Fraser River rear primarily in small tributaries which are highly susceptible to the thermal and hydrological impacts

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[1] It is feasible that global warming effects could influence Fraser pink and chum salmon by one of two mechanisms. First, warmer winter flows will reduce development time resulting in earlier emergence timing. The consequences of earlier emergence timing on subsequent marine survival and adult production are not presently known. Second, if high winter flows associated with global warming create flood conditions on lower river pink and chum spawning grounds (as occurred in the Chilliwack-Vedder system during the winter of 1990), this could seriously diminish pink and chum salmon egg-to-fry survival. Presumably, mainstem spawning areas would be less susceptible to winter flooding events.

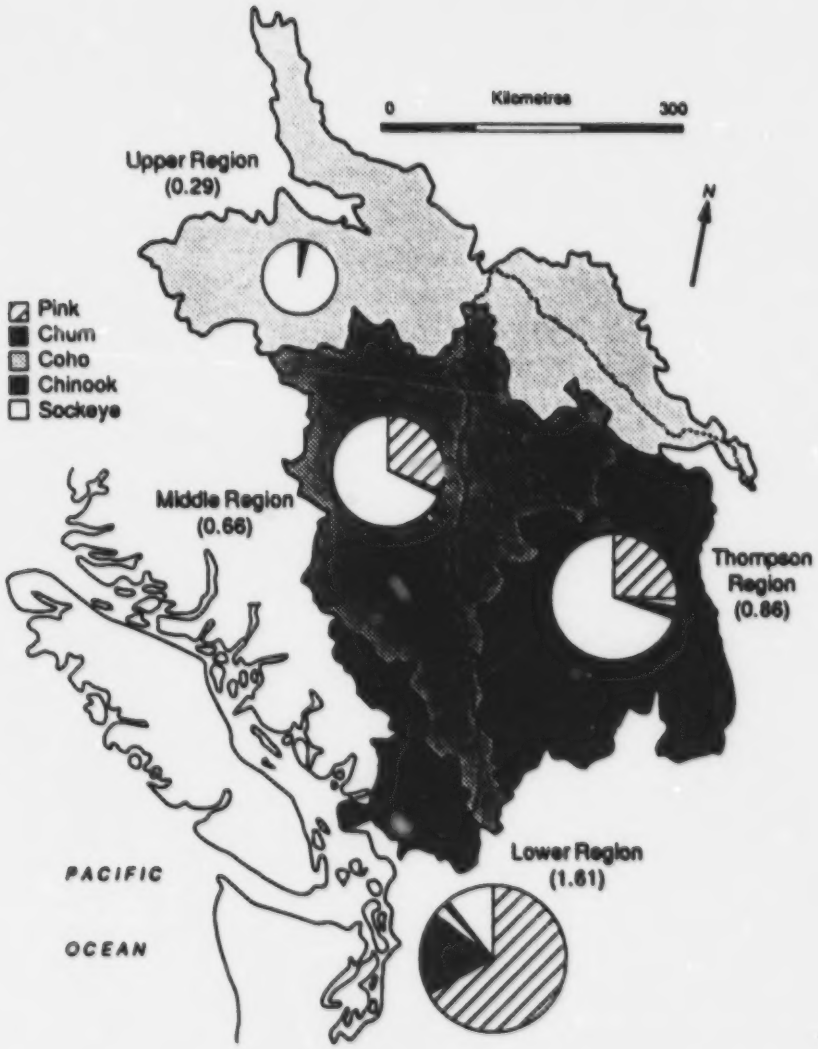


Figure 4.2. Average annual escapements to the four major regions of the Fraser River watershed. Reproduced from Northcote and Burwash (1991).

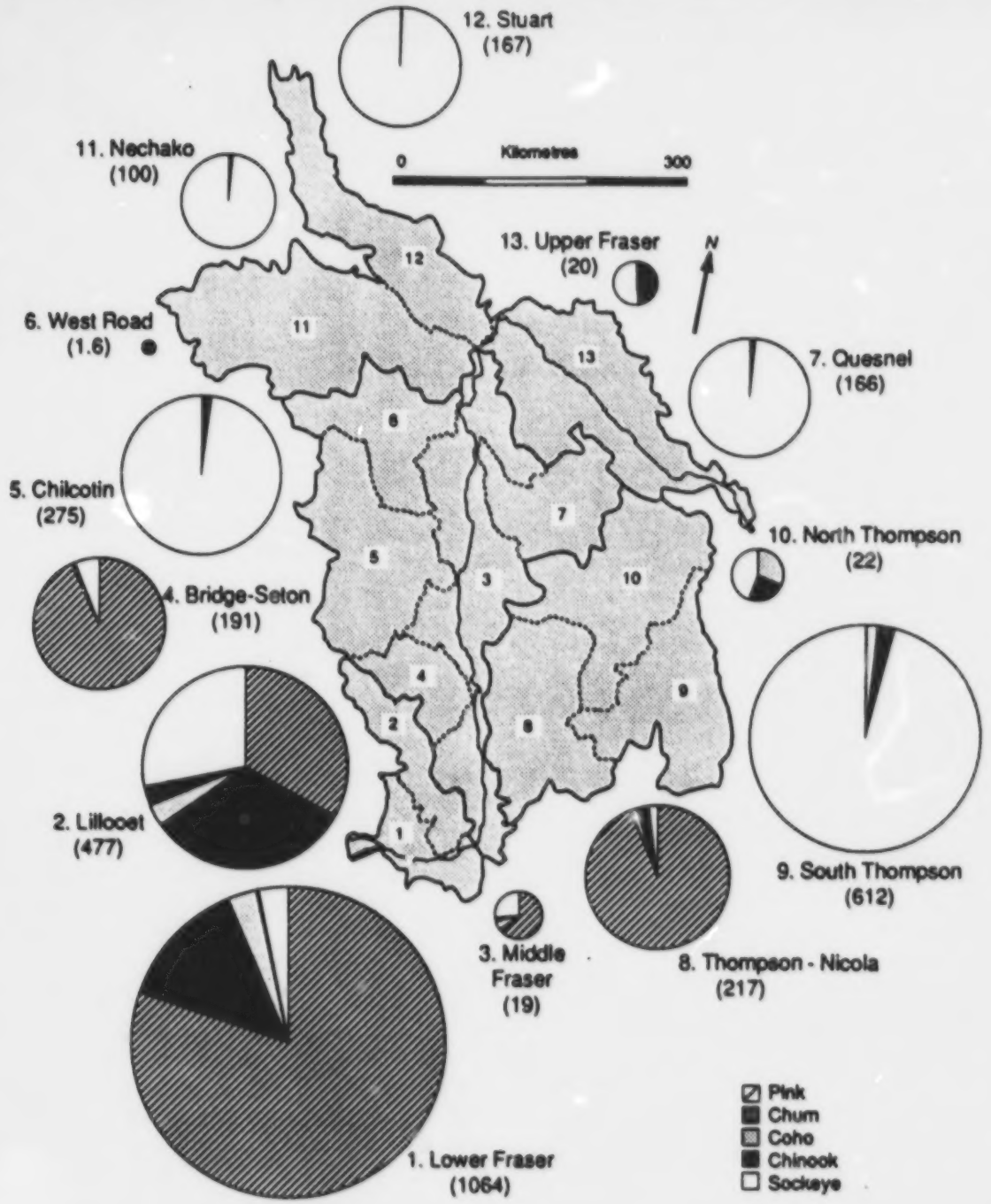


Figure 4.3. Average annual escapements (thousands; 1951-1989) of 5 species of Pacific salmon to 13 sub-basins within the Fraser River watershed. Reproduced from Northcote and Burwash (1991).

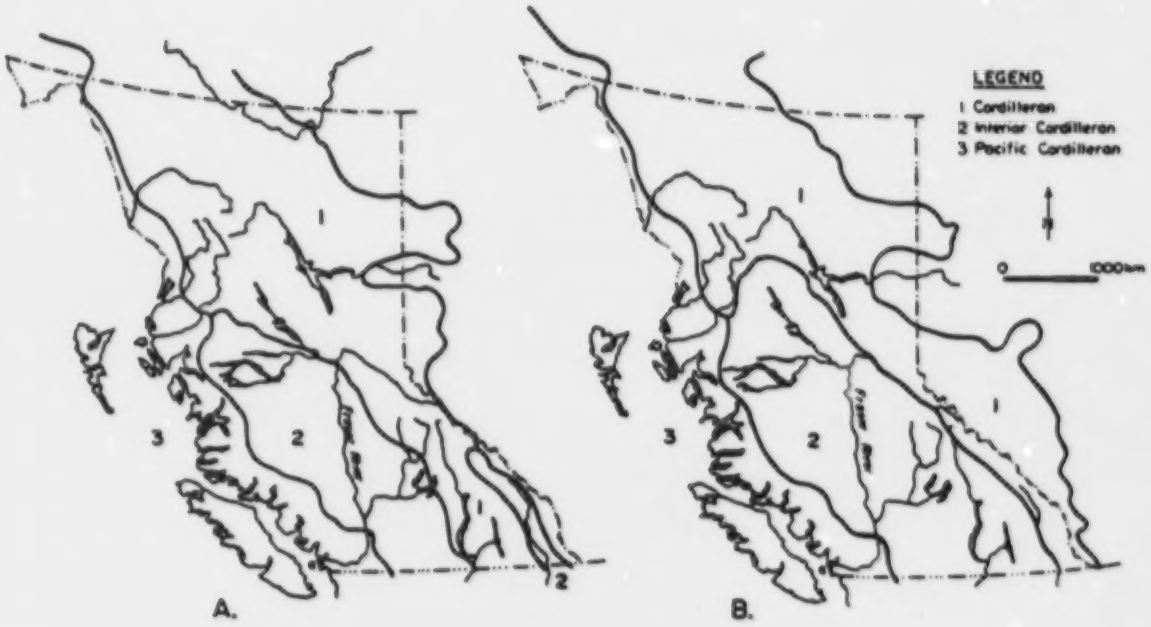


Figure 4.4. Possible changes in the boundaries of three ecoclimatic provinces within British Columbia following global warming. Reproduced from Zoltai (1988).

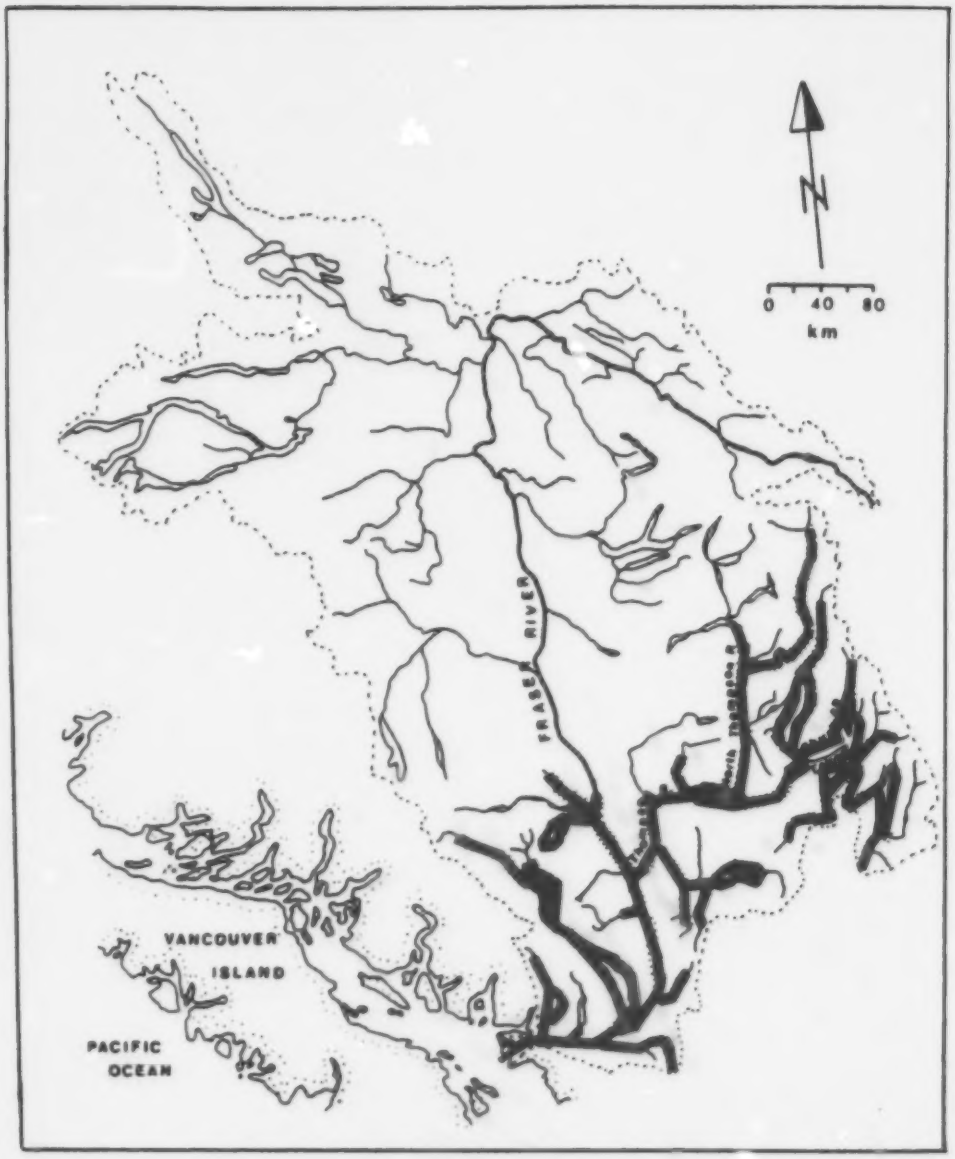


Figure 4.5. Approximate extent of coho salmon migration routes (shaded) in the Fraser River watershed. Reproduced from Fraser et al. (1982).

associated with global warming. Coho stocks within the Thompson Region would be particularly susceptible to such effects. Beacham and Murray (1990) compared embryonic development and alevin emergence in the five species of Pacific salmon, and concluded that coho would be the most vulnerable to global warming impacts, since coho appear to be adapted for low water temperatures during development. Warmer winter temperatures would lead to smaller coho alevin and fry sizes at emergence, thereby reducing juvenile survival.

Important spawning areas for chinook salmon are distributed throughout most of the Fraser River watershed (Table 4.1; Figure 4.6), and include the Harrison River population which is the single most numerous chinook population in B.C. Juvenile chinook salmon show diverse life history and migration patterns in the Fraser River watershed (Fraser et al. 1982) and often rear temporarily in nonnatal tributaries (i.e., tributaries with no chinook spawners) of the Nechako, Chilcotin, and Lower Fraser rivers (Murray and Rosenau 1989) as well as within the Fraser estuary (Levy and Northcote 1982). Chinook stocks from the Middle Region, Thompson Region, and the Upper Region of the Fraser River watershed would be particularly susceptible to climate warming effects.

The Fraser River also supports the largest stock complex of sockeye salmon within B.C., and may be capable of producing 30 million adults per annum (Henderson 1991), approximately three times the current average run size. Most sockeye populations within the Fraser show persistent cyclic fluctuations with four-year periodicity (Levy and Wood 1992) and future production estimates depend critically upon whether the populations can be managed to maintain strong runs on "sub-dominant" and "off-cycle" return years. By virtue of their freshwater life history (most Fraser sockeye juveniles spend their first year of juvenile existence within the pelagic zone of a nursery lake), sockeye spawning areas are located in close proximity, or within, relatively large nursery lakes (Figure 4.7). Sockeye populations within the Lower Region (Birkenhead River, Weaver Creek and five smaller stocks) are probably less vulnerable to global warming impacts than are sockeye stocks distributed throughout the remainder of the watershed. A preliminary analysis of climate warming impacts on the Adams River population (Henderson et al. 1992) suggests that climate warming could produce negative impacts on this important population. Since many of these Upper Region, Thompson Region, and Middle Region populations (including the Adams River, Horsefly, Chilko and Stuart sockeye stocks) support the bulk of the sockeye production within the watershed, it will be important to develop an effective management strategy for dealing with anticipated climate warming effects.

It seems likely that there will be regional disparities in global warming impacts on salmon within the Fraser watershed. Fraser River salmon populations within the interior portion of the watershed (Thompson Region, Middle Region, and Upper Region) that are highly dependent upon the freshwater environment for juvenile rearing are particularly vulnerable to future global warming effects. The latter includes

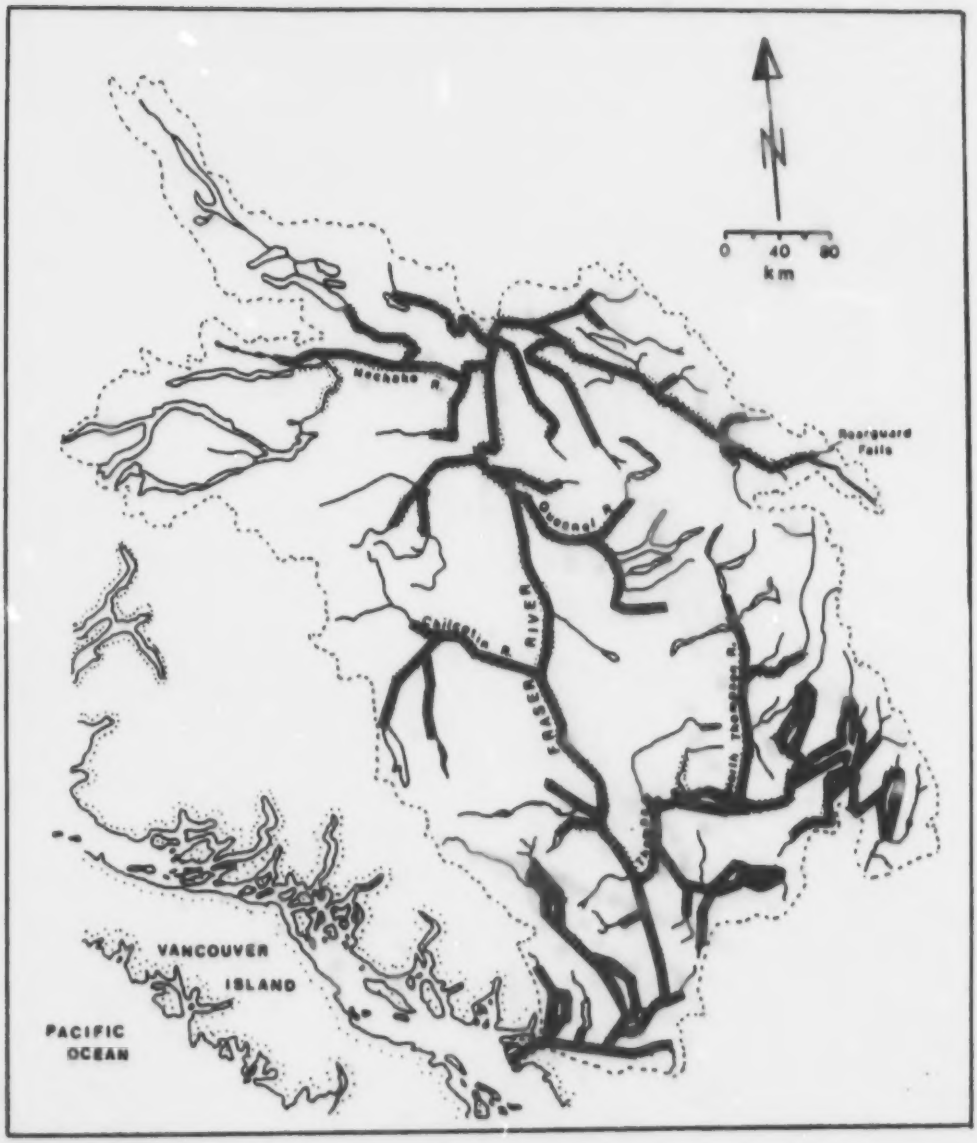


Figure 4.6. Approximate extent of chinook salmon migration routes (shaded) in the Fraser River watershed. Reproduced from Fraser et al. (1982).

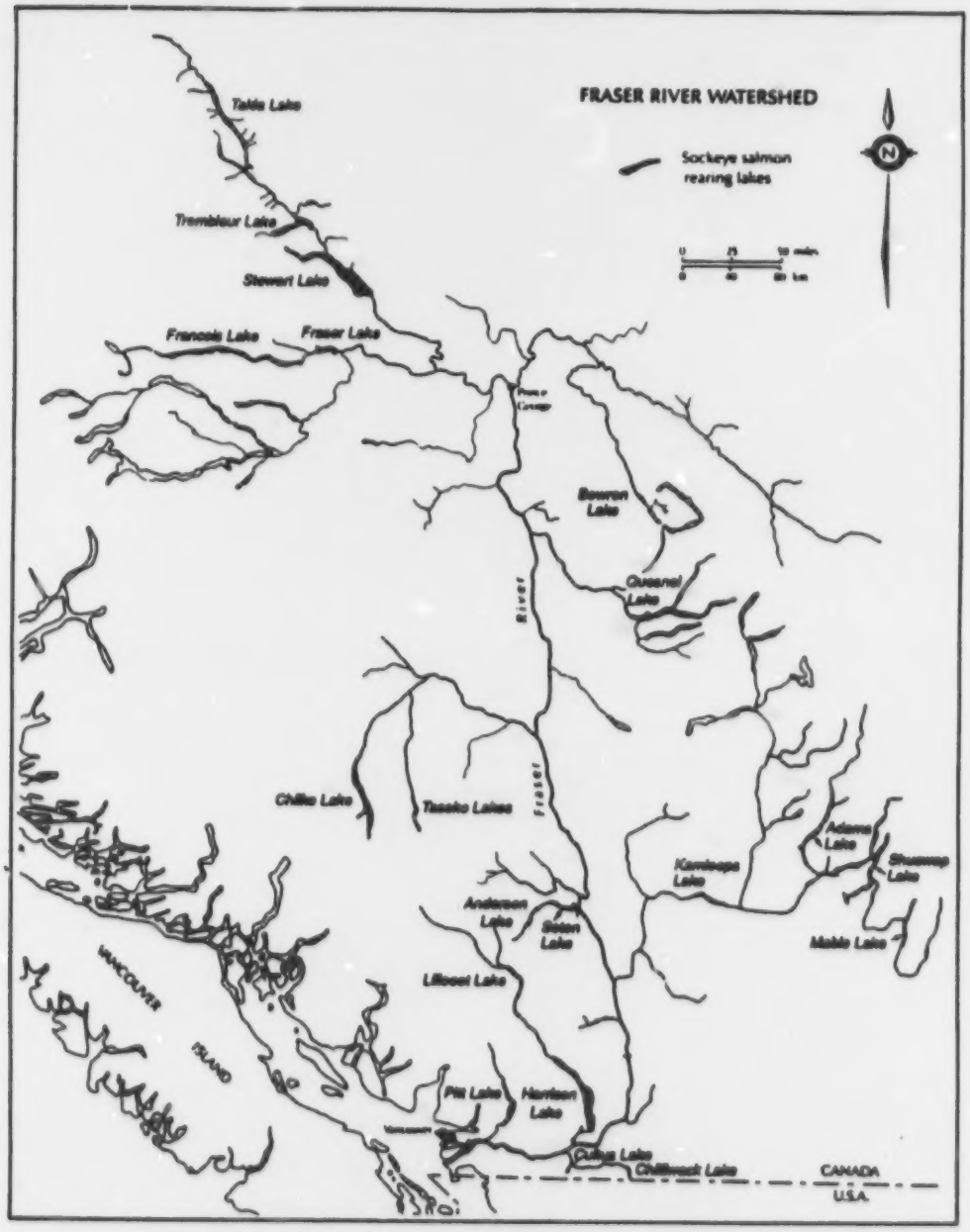
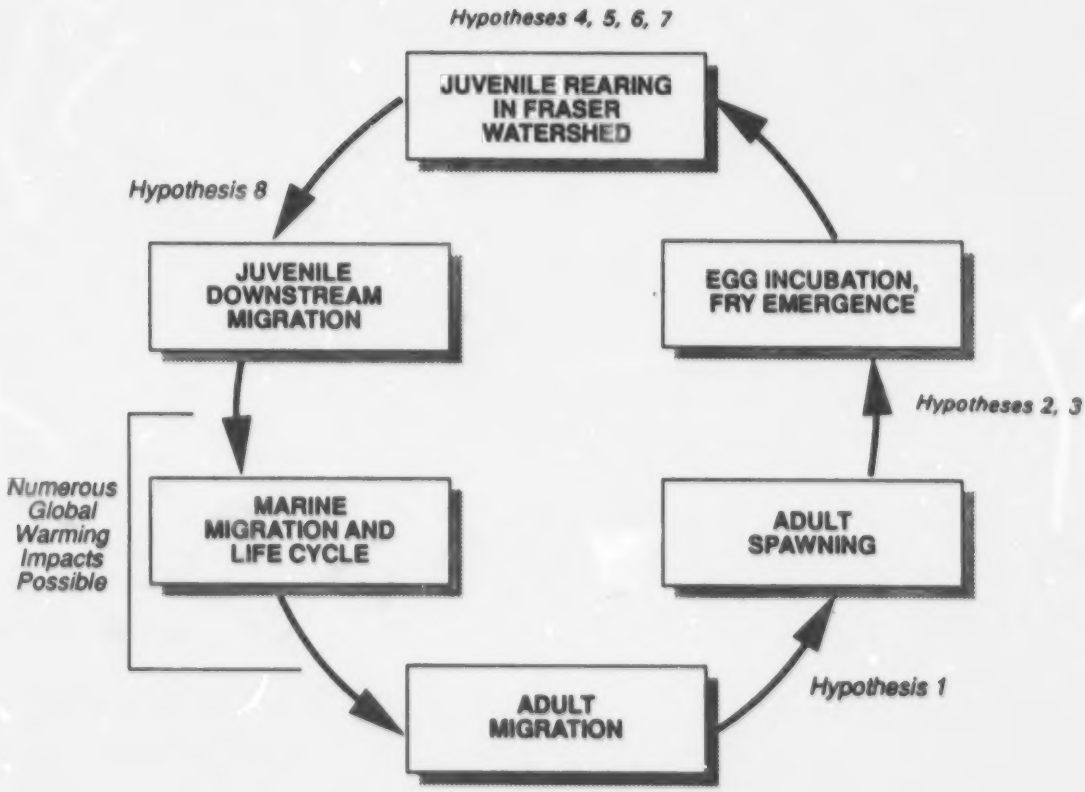


Figure 4.7. Major sockeye salmon rearing lakes within the Fraser River watershed. Reproduced from Gilhousen (1990).

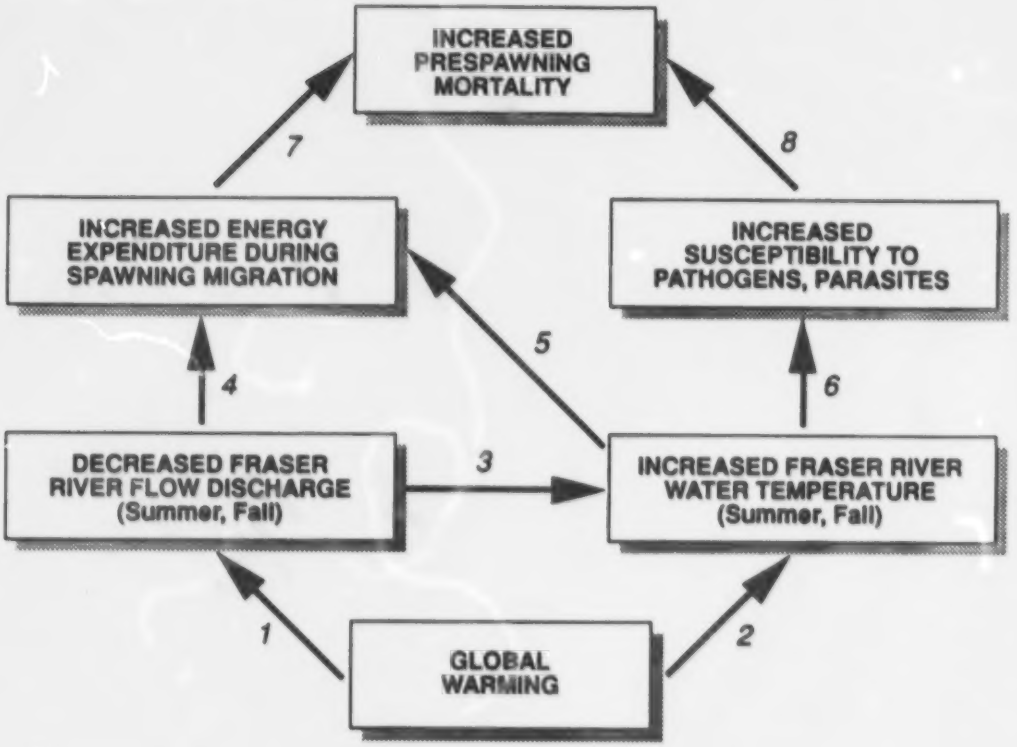
most of the chinook and sockeye populations, and many of the coho salmon stocks within the Fraser River watershed. Pink and chum salmon populations in the coastal portions of the watershed will be vulnerable to winter flooding impacts, and subsequent reductions in egg-to-fry survival.

5. Impact Hypotheses

The previous sections of this report describe current understanding of possible freshwater impacts of global warming in the Fraser River watershed, as well as the relative vulnerability of different salmon species to the predicted changes. To evaluate the importance of different impact mechanisms, this section of the report provides a set of impact hypotheses relating freshwater habitat changes associated with global warming, to the vulnerable species and stocks of salmon in the Fraser River watershed. These qualitative evaluations follow an approach suggested by Beansland and Duinker (1983) to relate human development activities (in this case, global warming) to "valued ecosystem components" (in this case, salmon in the Fraser River watershed) by a set of logically-structured functional linkages. The different impact hypotheses apply to the freshwater components of the life cycle of salmon as follows:



Hypothesis 1: Global warming will increase water temperatures and decrease flow conditions during salmon spawning migrations, causing additional prespawning mortality and reduced egg deposition.



Linkages

1 Global warming will result in decreased Fraser River flow discharge during the summer and fall months.

2 Global warming will result in increased Fraser River temperatures during the summer and fall months.

3 Reduced flows in the Fraser River and its tributaries will result in warmer water temperatures during the summer and fall months.

4 Reduced Fraser River flows will result in increased energy expenditures by adult salmon during their spawning migrations.

5 Increased Fraser River water temperatures will result in increased energy expenditures by adult salmon during their spawning migrations.

6 Increased Fraser River water temperatures will result in increased susceptibility of adult spawners to pathogens and parasites.

7 The increased energy expenditures during spawning migrations will result in increased prespawning mortality.

8 Higher infection rates from pathogens and parasites will result in increased pre-spawning mortality.

Introduction

While prespawning mortality occurs to some extent in all five salmon species in the Fraser River watershed, it occurs most commonly in sockeye and pink salmon. In general, sockeye salmon from the Upper Fraser River sub-basins, e.g., Early Stuart, Chilko and Stellako rivers, show higher prespawning mortality rates than those in other river systems (Gilhousen 1990). Both sockeye and pink salmon in the Fraser River have only a limited supply of energy available for migration and spawning activity (Brett 1973, Williams and Brett 1987). Since global warming will likely influence flow and temperature conditions in the Fraser River, it is important to evaluate possible energetic consequences and the impacts this might have on prespawning mortality rates.

Link 1: *Global warming will result in decreased Fraser River flow discharge during the summer and fall months.*

As reviewed in Section 3, summer and fall flows over much of the Fraser watershed will likely decrease in response to reduced summer precipitation levels and reduced winter snowpack levels. The net effect will be a reduction in the Fraser River discharge during summer and fall periods when adult salmon are migrating upstream to tributary spawning grounds.

Link 2: *Global warming will result in increased Fraser River temperatures during the summer and fall months.*

Higher atmospheric temperatures associated with global warming will likely cause higher stream and river temperatures. Heat transfer from air is substantial in rivers and streams (as opposed to lakes where wind mixing is important) due to the relatively

high air/water interface area. It is therefore likely that global warming will result in warmer Fraser River temperature conditions during summer and fall months.

Link 3: *Reduced flows in the Fraser River and its tributaries will result in warmer water temperatures during the summer and fall months.*

With all other variables held equal, a stream with low flow discharge will achieve higher temperatures than the same stream under high flow conditions. This is because the air/water interface area is proportionately greater under low flow conditions. It is therefore likely that stream temperatures will increase due to both atmospheric temperature increases and also to more efficient heating related to the anticipated flow reductions.

Link 4: *Reduced Fraser River flows will result in increased energy expenditures by adult salmon during their spawning migrations.*

Fish passage up the Fraser River involves upstream-oriented migration covering hundreds of kilometers. Constraints on upstream fish passage are severe at Hell's Gate where the International Pacific Salmon Fisheries Commission has constructed fishways to promote favourable migration conditions. Flow velocity (as opposed to discharge) is a primary determinant of upstream fish passage success. In general, lower discharge creates lower velocity conditions which enhance upstream fish passage. While Fraser River salmon might benefit from lower velocities, extreme low flow conditions may occur below the minimum design capacity for the existing fishways. If this occurs, it would be necessary to build additional fishways, or modify the operation of existing ones.

Link 5: *Increased Fraser River water temperatures will result in increased energy expenditures by adult salmon during their spawning migrations.*

Due to temperature-related metabolic factors, energetic expenditures of ectothermic organisms, e.g., salmon, are greater under warmer temperatures. The relationship between energy expediture during migration and temperature is exponential, implying that small temperature increases may have substantial effects on energy expenditures.

Link 6: *Increased Fraser River water temperatures will result in increased susceptibility of adult spawners to pathogens and parasites.*

A number of studies (e.g., Fujihara et al. 1971, Holt et al. 1975, Groberg et al. 1978) have shown a temperature effect on pathogenic infection rate in salmonids for several bacterial pathogens, including *Aeromonas salmonicida* and *Flexibacter columnaris*. Thermal effects on parasitic infection rates in salmonids are not well documented, although it seems likely that there would be a positive relationship based on known salmon parasite life histories and modes of transmission. Because of these

relationships, this linkage seems highly likely.

Link 7: *The increased energy expenditures during spawning migrations will result in increased prespawning mortality.*

Most of the surplus energy reserves obtained by salmon during the marine life history phase are expended during upstream migration and spawning. Fraser River salmon, particularly pink and sockeye, have only a minimal surplus energy reserves above that which is required for successful migration and spawning. It is therefore likely that increased energy expenditure during migration will result in increased prespawning mortality rates.

Link 8: *Higher infection rates from pathogens and parasites will result in increased prespawning mortality.*

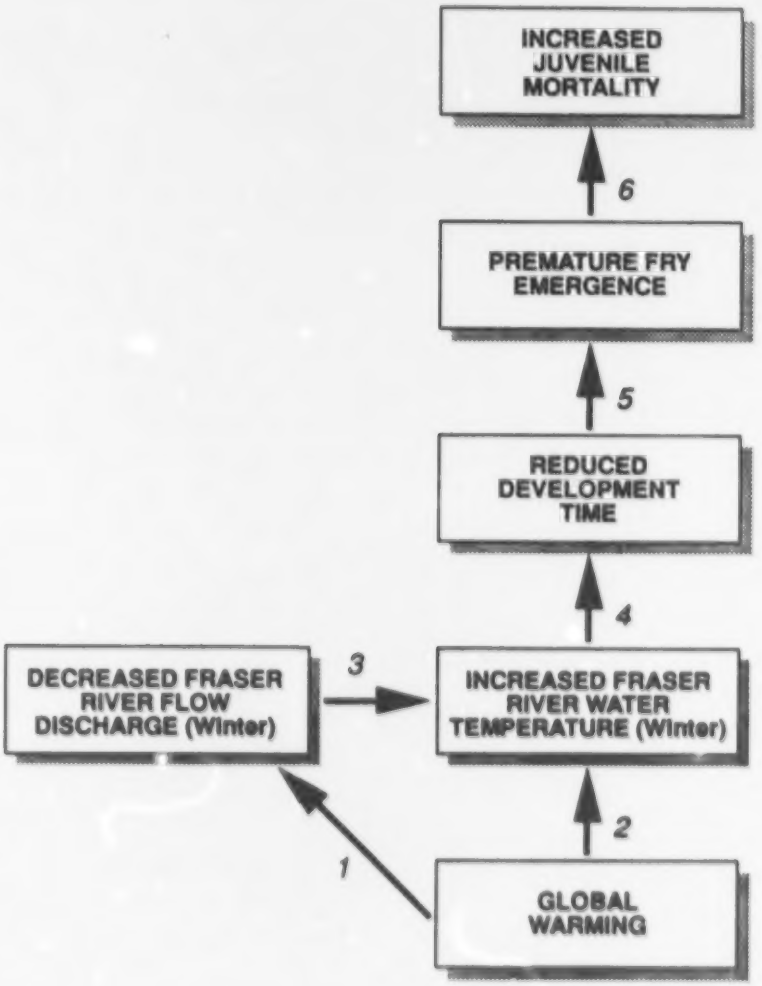
This linkage is a logical extension of linkage #6.

Conclusion

This impact hypothesis seems highly probable because of higher Fraser River water temperatures that may occur following additonal climate warming. For several Upper Fraser River sockeye stocks, direct relationships exist between the measured water temperature at Hell's Gate and prespawning mortality rates (Gilhousen 1990). The pathway whereby flow reductions increase energy expenditures and cause increased prespawning mortality seems unlikely since lower flow discharges (and velocities) are associated with reduced energy expenditures.

Gilhousen (1990) recommends a temperature value below 15°C for maximum survival of maturing sockeye during their river migration. Because of the strong temperature influence on prespawning mortality rate, early migrating sockeye stocks which swim upstream during mid-summer are particularly vulnerable to climate change impacts. The latter includes both the Early Stuart and Nadina stocks.

Hypothesis 2: Global warming will increase water temperatures during egg incubation stages, causing premature fry emergence and increased fry-to-smolt mortality.



Linkages

1 Global warming will result in decreased Fraser River flow discharge during the summer and fall months.

2 Global warming will result in increased Fraser River temperatures during the summer and fall months.

3 Reduced flows in the Fraser River and its tributaries will result in warmer water temperatures during the summer and fall months.

4 Increased Fraser River water temperatures will result in reduced egg development time.

5 Reduced egg development time will result in premature fry emergence.

6 Premature fry emergence will increase juvenile mortality rates.

Introduction

For ectotherms, environmental temperature has a major influence on development rate. Warmer winter temperatures in tributaries may effectively speed up egg development and result in earlier emergence timing, which in turn will influence juvenile survival rate. In Carnation Creek, B.C., stream temperatures increased as a result of logging and resulted in early fry emergence, longer growing season, and larger coho fry (Holtby 1988). However, the effects of warmer stream temperatures on coho production were complex and partially negative. This hypothesis considers the likelihood of such effects in the Fraser River watershed.

Link 1: *Global warming will result in decreased Fraser River flow discharge during the winter months.*

For the Pacific Northwest during winter periods, most GCMs forecast increases in precipitation levels, coupled with an increase in the proportion of precipitation falling as rain. Therefore, this linkage is unlikely.

Link 2: *Global warming will result in increased Fraser River temperatures during the winter months.*

In most Interior Fraser River sub-basins, winter stream flows originate from groundwater baseflows or lake water runoff. In general, groundwater temperatures are predicted to follow atmospheric temperature increases (Meisner et al. 1988). Depending upon the exact location within the Fraser watershed and whether the adjacent lakes and streams are ice-covered, winter climate warming effects could range from negligible to substantial. This linkage is difficult to evaluate from a general perspective, and winter stream temperature alterations need to be assessed on a site-specific basis.

Link 3: *Reduced flows in the Fraser River and its tributaries will result in warmer water temperatures during the winter months.*

This linkage is unlikely, by virtue of the unlikelihood of linkage #1.

Link 4: *Increased Fraser River water temperatures will result in reduced egg development time.*

Development time in Pacific salmon (both time to hatching, as well as time to emergence) decreases exponentially as a function of temperature (Beacham and Murray 1990). Therefore, this linkage is valid.

Link 5: *Reduced egg development time will result in premature fry emergence.*

The form of the temperature-development rate relationship in salmon will dictate whether this linkage is significant. Brannon (1987) describes the compensation in sockeye salmon development rate which serves to effectively stabilize fry emergence timing under different temperature conditions. Curvilinear relationships between degree days (one degree day = 1°C> freezing/24h) to yolk absorption and temperature indicates that salmonid development rates change as a function of temperature. This compensation effect will stabilize the development rate of salmonid embryos when exposed to temperature variations during incubation. This linkage is therefore qualitatively correct, and the magnitude of the effect could be evaluated from existing temperature-development rate relationships.

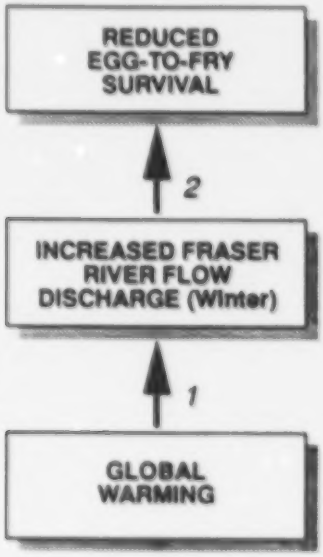
Link 6: *Premature fry emergence will increase juvenile mortality rates.*

Brannon (1987) states that spawning timing in sockeye salmon is a genetically fixed characteristic for each population to ensure optimum emergence timing under the full range of local environmental conditions. If this argument is valid, then deviations from optimal fry emergence timing should result in juvenile survival rate reductions since the emergence timing will occur prior to the "optimum" as determined by natural selection.

Conclusion

The influence of temperature on salmonid egg development rate and alevin survival has been well studied. However, the physical (climatic and hydrological) processes controlling winter stream temperature conditions during egg incubation are not well understood. The validity of this hypothesis hinges on linkage #2, the influence of global warming on winter water temperatures. This linkage requires additional site-specific hydrological information before the hypothesis can be rejected.

Hypothesis 3: Global warming will increase the severity and frequency of winter floods, thereby reducing egg-to-fry survival rates.



Linkages

1 Global warming will result in increased Fraser River flow discharge during winter months.

2 Increased Fraser River flow discharge during winter months will result in reduced egg-to-fry survival.

Introduction

Possible hydrological effects of global warming in the Fraser River watershed include the alteration of seasonal flow discharge patterns, with lower flows in summer months, and higher flows in winter periods. If the winter increases are substantial and result in an increased frequency of flood events, this could have a deleterious impact on salmon fry production. This hypothesis considers the likelihood of such an effect due to global warming.

Link 1: *Global warming will result in increased Fraser River flow discharge during winter months.*

This linkage is valid since the GCMs forecast increased winter precipitation and discharge (more precipitation as rain, and less as snow). Winter flooding will likely be most severe in the Coastal Mountain hydrologic region (Figure 3.2) of the Fraser watershed where substantial winter precipitation increases are anticipated.

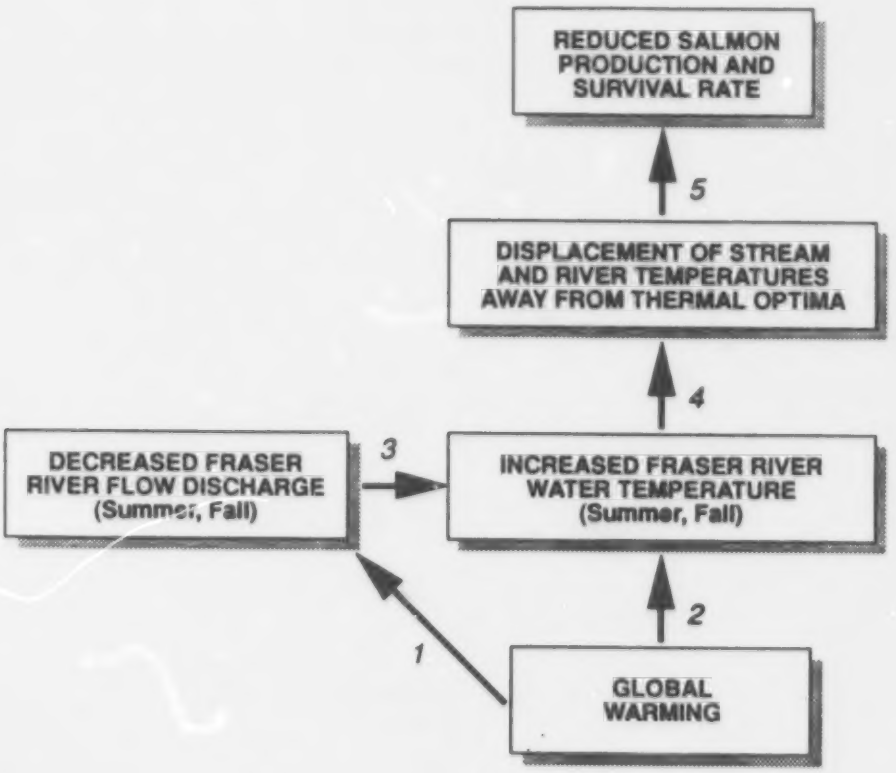
Link 2: *Increased Fraser River flow discharge during winter months will result in reduced egg-to-fry survival.*

The relationship between flow discharge and salmon egg-to-fry survival is probably curvilinear, with maximum survival rate at some optimal flow level. Flows beyond this optimal level (i.e., flooding) probably decrease egg-to-fry survival due to scouring effects and the associated physical changes to spawning bed configuration. Therefore, this linkage is qualitatively correct, provided that the flow discharges exceed the optimal level for egg-to-fry survival.

Conclusion

This hypothesis seems highly probable within the coastal portion of the Fraser watershed where the greatest increases in winter stream discharge can be anticipated. Pink and chum salmon are the two species most vulnerable to winter flooding impacts by virtue of their concentration within the Coastal Mountain hydrologic region.

Hypothesis 4: Global warming will increase stream and river water temperatures away from the thermal optima for salmon, creating suboptimal salmon habitat conditions in the Fraser River.



Linkages

1 Global warming will result in decreased Fraser River flow discharge during the summer and fall months.

2 Global warming will result in increased Fraser River temperatures during the summer and fall months.

3 Reduced flows in the Fraser River and its tributaries will result in warmer water temperatures during the summer and fall months.

4 Fraser River water temperatures will be less suitable for salmonids than present-day temperature conditions.

5 Suboptimal temperature conditions will result in reduced salmon production and survival rates.

Introduction

Both coho and chinook salmon within the Fraser River watershed are dependent upon stream and river habitats for juvenile rearing during their first year of life. Summer warming impacts in stream habitats could influence smolt production directly, by shifting summer temperature conditions away from values which optimize growth rate. Due to positive relationships between smolt body size and marine survival rate, freshwater growth rate reductions would be expected to have negative impacts on salmon production.

Link 1: *Global warming will result in decreased Fraser River flow discharge during the summer and fall months.*

See Hypothesis 1, Link 1.

Link 2: *Global warming will result in increased Fraser River temperatures during the summer and fall months.*

See Hypothesis 1, Link 2.

Link 3: *Reduced flows in the Fraser River and its tributaries will result in warmer water temperatures during the summer and fall months.*

See Hypothesis 1, Link 3.

Link 4: *Fraser River water temperatures will be less suitable for salmonids than present-day temperature conditions.*

A temperature close to 15°C provides physiological optimum conditions for juvenile sockeye salmon, and other salmon species probably have similar thermal requirements. For much of the year (winter, spring, and fall months) water temperatures will occur below this value, even in the face of significant global warming. However, during summer months, there is a high probability of extended periods when temperature conditions may exceed this optimum value, particularly where flow reductions induce higher temperatures (linkages #1 and #3).

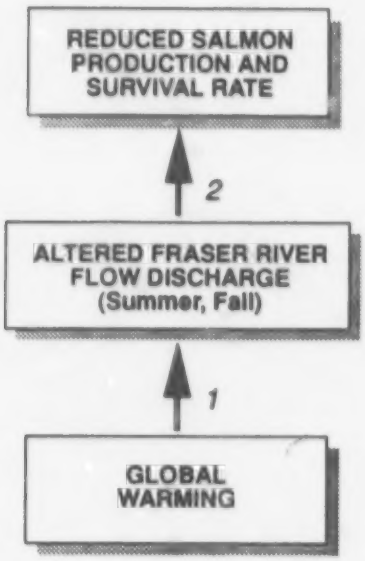
Link 5: *Suboptimal temperature conditions will result in reduced salmon production and survival rates.*

Since much of the body growth of 0+ juvenile salmon occurs during summer periods, water temperature increases could result in reduced growth rates and smaller smolt body size. Smaller smolt body size may influence salmon marine survival in a negative direction because of direct relationships between smolt body size and survival rate (Henderson and Cass 1991). Additionally, reductions in late-summer body size of coho and chinook could also influence smolt production if the ability to survive over-winter is related to body size at the end of the first growing season (as occurs in several warmwater temperate fish species - Shuter and Post 1990). This linkage would seem likely if growth rate reductions occur in response to suboptimal temperature conditions.

Conclusion

This impact hypothesis is relevant for both coho and chinook salmon within the Interior subbasins of the Fraser River watershed. With warmer stream and river temperature conditions, juvenile chinook and coho will concentrate in the available coldwater refuges, e.g., pools, groundwater inflows, for an increased duration during warm summer periods. In addition to the direct effects on freshwater survival, indirect influences on survival and production due to growth rate reductions may also be significant.

Hypothesis 5: Global warming will alter the timing and volume of stream flow discharges, reducing the capability of streams to produce juvenile salmon.



Linkages

1 Global warming will result in altered Fraser River flow discharge during the summer and fall months.

2 Alterations in stream discharge will negatively affect juvenile salmon production and survival rates in the Fraser River.

Introduction

In addition to thermal effects on streams (considered under hypothesis #4), altered atmospheric temperature, precipitation timing, and soil moisture conditions will greatly influence the volume and timing of flow discharge. Since both chinook and coho salmon are dependent upon adequate, yearlong instream flows for juvenile rearing purposes, they are potentially susceptible to reductions in flow discharge that are associated with global warming.

Link 1: *Global warming will result in altered Fraser River flow discharge during the summer and fall months.*

See Hypothesis 1, Link 1.

Link 2: *Alterations in stream discharge will negatively affect juvenile salmon production and survival rates in the Fraser River.*

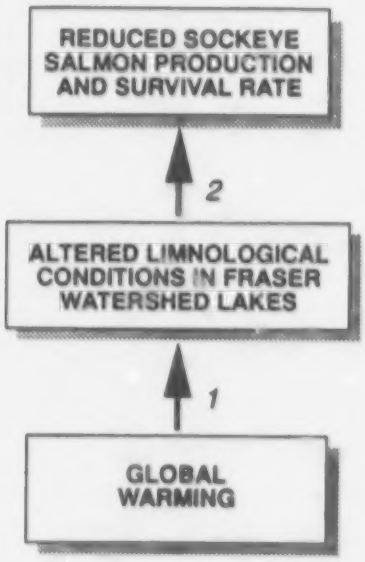
This linkage applies to stream-resident juvenile salmonids (coho, chinook) which are limited by the amount of suitable rearing habitat under low flow conditions.

Conclusion

There is considerable regional variation in the seasonal timing of low flow periods in the Fraser watershed depending on a number of climatic and hydrologic parameters (Moore 1991). Some tributaries, e.g., Salmon River near Langley, have lowest discharges in late-summer periods, while others, e.g., McGregor River, have lowest discharges in mid-winter.

Streams and tributaries which have low flows in summer-fall would be most susceptible to possible reductions in summer precipitation and shifts in the accumulated snowpack. Resident juvenile coho and chinook within such streams would be vulnerable to flow reductions, particularly if there is a present constraint on the amount of available rearing habitat. By virtue of their spawning distribution (Figures 4.5-4.6), coho would be susceptible to summer flow reductions in the Thompson Region, while chinook might be vulnerable to such effects within the Thompson, Upper and Middle Regions (Figure 4.1) of the Fraser watershed.

Hypothesis 6: Global warming will cause altered limnological conditions in Fraser lakes, thereby reducing their suitability as nursery habitats for sockeye salmon juveniles.



Linkages

1 Global warming will result in altered limnological conditions in Fraser River watershed lakes.

2 Alterations in lake conditions will negatively affect juvenile sockeye salmon production and survival rates in the Fraser River.

Introduction

Many large lakes (> 10 km^2) are utilized as rearing habitats by juvenile sockeye salmon within the Fraser River watershed (Figure 4.7). Virtually all major sockeye stocks spawn within lake tributary inflows or outflows. Global warming will alter environmental conditions within Fraser River lakes through increases in mean annual atmospheric temperature, thereby affecting lake heat budgets. Changes in the volume and timing of lake tributary inflow discharges will greatly influence lake turnover times, nutrient concentrations, and production processes. Such limnological effects may influence juvenile sockeye production and survival rates.

Link 1: *Global warming will result in altered limnological conditions in Fraser River watershed lakes.*

Based on the empirical observations of Schindler et al. (1990) and general limnological principles, the predicted increases in atmospheric temperature and precipitation for the Fraser watershed will likely produce altered limnological conditions. Henderson et al. (1992) considered possible global warming consequences on Shuswap Lake, the lake nursery for the Adams River sockeye population. Anticipated changes in nutrient inputs and stratification were predicted to change the production characteristics of Shuswap Lake towards a more oligotrophic system.

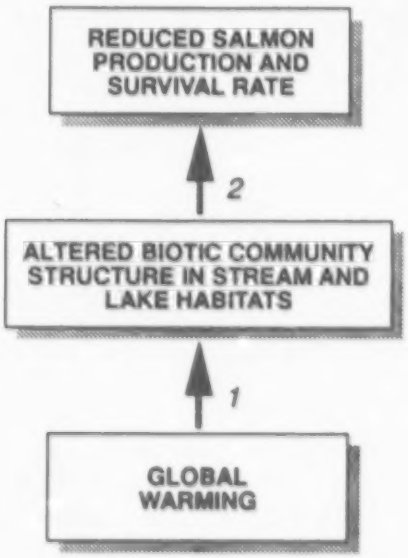
Link 2: *Alterations in lake conditions will negatively affect juvenile sockeye salmon production and survival rates in the Fraser River.*

Henderson et al. (1992) concluded that global warming would result in reduced zooplankton food availability within Shuswap Lake for juvenile sockeye due to altered planktonic production rate and community structure. Further, increased lake heating may result in an uncoupling of the sockeye feeding niche and thermal niche within Shuswap Lake, due to the concentration of zooplankton food organisms in warm surface epilimnetic waters during the mid-summer growing season. These effects were predicted to result in reduced Adams River sockeye production and survival rate.

Conclusion

This hypothesis seems likely although there is uncertainty concerning both the magnitude and direction of the anticipated effects. Twenty years of empirical observations in a northwestern Ontario lake indicated an increase in lake turnover time and increases in nutrient concentration simultaneous with an average lake temperature increase of 2°C (Schindler et al. 1990). These results contrast the global warming predictions for Shuswap Lake by Henderson et al. (1992) who suggest a reduction in overall nutrient concentrations due to altered runoff patterns. It may be safe to conclude that lakes may respond differently to global warming effects depending upon regional atmospheric temperature, precipitation and runoff changes.

Hypothesis 7: Global warming will increase water temperatures resulting in altered aquatic community structure, adversely affecting salmon populations in the Fraser River.



Linkages

1 Global warming will result in altered biotic community structure in Fraser River watershed stream and lake habitats.

2 Alterations in biotic community structure will negatively affect juvenile salmon production and survival rates in the Fraser River.

Introduction

It is presently difficult to extrapolate from existing regional climate scenarios to derive reasonable hydrological predictions under a warmer and wetter global climate. The difficulty of deriving accurate predictions of biotic responses at the community or ecosystem level is magnified manyfold and may be impossible for all practical purposes. Nevertheless, there is a high likelihood for shifts in biotic community structure as a result of global warming even if they are not readily predicted. This impact hypothesis considers the prospect of shifts in aquatic community structure within the Fraser River watershed.

Link 1: *Global warming will result in altered biotic community structure in Fraser River watershed stream and lake habitats.*

Altered biotic community structure can occur by changes in the relative abundance of existing species, and also by range extensions and invasions of exotic species currently distributed to the south of the Fraser River watershed. Community shifts seem likely at every trophic level from primary producers, through to piscivores. In general, the predicted warming will tend to favour warmwater species, and will create negative impacts for coldwater species, particularly along the southern margins of their geographical range. The latter includes all five salmon species within the Fraser watershed, with the possible exception of chinook salmon which are presently numerous as far south as the Ventura River in Southern California, and coho salmon that presently extend as far south as Southern Coastal Oregon.

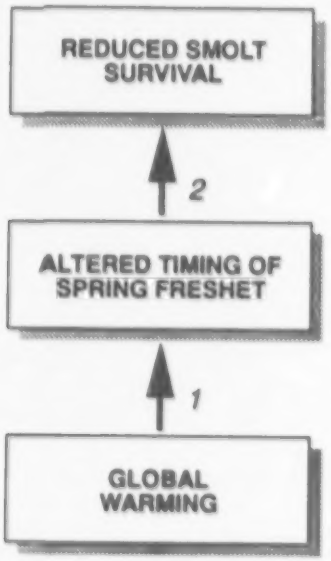
Link 2: *Alterations in biotic community structure will negatively affect juvenile salmon production and survival rates in the Fraser River.*

This linkage is complicated to evaluate since it involves the set of many hundreds of species which interact with Fraser watershed salmon in both direct and indirect ways. Altered community interactions associated with global warming could be negative and severe (e.g., population increases in warmwater piscivores like northern squawfish), neutral, or even positive (e.g., shift in zooplankton species composition favouring large-bodied cladocerans).

Conclusion

On balance, because salmon are "coldwater" species, it seems likely that community shifts will be mostly unfavourable for Fraser watershed salmon due to the climatic enhancement of warmwater competitors and predators.

Hypothesis 8: Global warming will shift the timing of the spring freshet, effectively increasing the mortality rate of salmon smolts as they migrate down the Fraser River.



Linkages

1 Global warming will shift the seasonal timing of the spring freshet in the Fraser River.

2 Alterations in the timing of the spring freshet will negatively affect salmon smolt survival rates in the Fraser River and the marine environment.

Introduction

In a simulation study of climate warming impacts upon Yakima sub-basin (Columbia River) chinook salmon, Chatters et al. (1991) found that the model results were very sensitive to reductions in chinook smolt survival during outmigration due to a shift in the timing of the spring freshet. This impact hypothesis considers the likelihood of such a mechanism operating on salmon within the Fraser watershed.

Link 1: *Global warming will shift the seasonal timing of the spring freshet in the Fraser River.*

Simulation modeling results for the Sacramento-San Joaquin River watershed (Lettenmaier and Gan 1990) showed that the hydrologic response in the catchments was dominated by temperature-related changes in snowmelt. In particular, winter runoffs were predicted to increase and spring-summer runoffs were predicted to decrease. In the Columbia River watershed, paleohydrology data suggest that the spring freshet ended three to four weeks earlier than it does today (Chatters et al. 1991). Moore (1991) compared Fraser River freshet timing during warm (1938-1947) and cold (1963-1972) decades and found that the timing of the freshet occurred earlier in the spring during the warm decade. These studies all substantiate the present linkage and suggest that with global warming, peak Fraser River flows will occur earlier during the year than occurs at present.

Link 2: *Alterations in the timing of the spring freshet will negatively affect salmon smolt survival rates in the Fraser River and the marine environment.*

Recent analysis on the influence of the timing of smolt outmigration in Chilko Lake sockeye suggests that early, narrowly-dispersed migration timing is associated with higher marine survival (M. Henderson, Dept. of Fisheries and Oceans, unpubl. data). These trends may be related to the timing of piscivore aggregations in the marine environment. The Chilko Lake sockeye observations contrast those obtained by Holtby (1988) who documented earlier smolt migrations in Carnation Creek coho (as a result of logging-related stream temperature increases) which may have resulted in decreased smolt survival. It is possible that this linkage varies regionally depending upon salmon species and watershed location on the Pacific coast.

Conclusion

While linkage #1 of this hypothesis can be substantiated, evidence supporting linkage #2 appears to be somewhat ambiguous. The hypothesis can neither be accepted nor rejected at the present time. It may be possible to further test this hypothesis with existing juvenile outmigration timing and marine survival data for different species and stocks of salmon from the Fraser River watershed.

6. Management Recommendations

The Fraser River Environmentally Sustainable Development Task Force has defined seven specific goals for sustainable fisheries development in the Fraser River watershed, including:

A. Maintain ecological diversity of the basin (consistent with the no net loss principle of the Fish Habitat Management Policy and recognizing the finite productive capacity of the basin) by:

A1. Avoiding irreversible human changes to fish-producing habitats.
A2. Maintaining the genetic diversity of fish stocks.
A3. Maintaining the physical and biological diversity of fish habitats.
A4. Capitalizing on opportunities to restore, create, or increase production capacity through habitat management (work for a net gain in the productive capacity of fish habitat).

B. Maximize the net economic benefits that can be derived from the fishery resource by:

B1. Maximizing the net economic value of commercial, sport, and native fisheries in the Fraser Basin.
B2. Maximizing the non-consumptive values of fishery resources such as existence and option value.
B3. Distributing fishery net benefits in a fair and equitable manner.

These goals implicitly assume that the present-day climate will extend into the future, at least for the duration of the planning horizon duration considered by the task force. Because the prospect of climate change within the Fraser basin is real and significant, there are important implications for the first four task force goals (A1-A4) which are discussed below.

A1. Avoiding irreversible human changes to fish producing habitats. Due to the global nature of the problem, it is not feasible to avoid climate change impacts in the Fraser watershed. Climatologists point out that even if global carbon emissions were stabilized (which they are not), the enhanced greenhouse effect associated with past carbon emissions has already committed the Earth to significant warming well into the 21st century. Future climate changes are essentially irreversible unless there are radical alterations to current patterns of industrialization and fossil fuel use. Since it is not possible to avoid climate-related changes to fish habitats within the Fraser watershed, adaptation appears to be the most relevant fisheries management policy (Healey 1990).

A2. Maintaining the genetic diversity of fish stocks. Protection of regional biodiversity will become an increasingly important topic, particularly within temperate and polar ecosystems, if climate change scenarios materialize as predicted. The Fraser River ESD Task Force maintains that no fish stock, however small, will be arbitrarily written off. However, if temperate fish distribution patterns shift northward, and aquatic habitat conditions in the Fraser watershed become unsuitable for salmon, by implication we may have to (reluctantly) accept local stock extinctions.

A3. Maintaining the physical and biological diversity of fish habitats. The prospect of climate change within the Fraser watershed implies that fish habitats will undergo physical and biological changes as temperatures increase and precipitation is redistributed. Conservation of habitat diversity is possible within the context of a given set of climatic conditions; if climate changes, then the occurrence of specific habitat features, their distribution and spatial extent will also shift. Shifts in future fish habitat availability in a warmer Fraser River watershed with altered precipitation conditions are difficult to anticipate at present.

A4. Capitalizing on opportunities to restore, create, or increase production capacity through habitat management (work for a net gain in the productive capacity of fish habitat). It is likely that the nature of the habitat restoration opportunities will shift from those of the present. As well as creating new habitat constraints, climate change will create certain new habitat opportunities; strategies need to be adopted so that positive fish production opportunities are recognized and developed at an early stage.

Since prevention of global warming is not feasible, and mitigation of global warming effects is undesirable because of a high risk of failure over the long term, adaptation to global warming impacts provides the most realistic fisheries policy option. Due to the inherently high value of Fraser River salmon resources, an actively adaptative habitat management policy is preferable to a passive one. Such a policy would include a monitoring strategy to detect future climate warming impacts when they occur, and also an experimental probing strategy designed to identify new fish production opportunities (Healey 1990).

The impact hypotheses (Section 5) identify specific freshwater life history stages where impacts might be anticipated. These include: 1) prespawning mortality of migrating adult salmon stocks; 2) impacts associated with premature salmon fry emergence; 3) winter flooding impacts on pink and chum salmon in the Lower Region; 4) impacts of stream temperature shifts on coho and chinook salmon juveniles in the Middle, Thompson and Upper regions; 5) impacts of stream flow changes on coho and chinook salmon juveniles in the Middle, Thompson and Upper Regions; 6) impacts on juvenile sockeye salmon in their lake nurseries; 7) general aquatic community changes; and 8) impacts associated with shifts in freshet timing. Additionally, there will be climate change impact "surprises" which are difficult to anticipate or predict.

It is recommended that fisheries habitat managers identify a set of index stocks of salmon in the Fraser River for long- term monitoring of climate warming impacts. This monitoring should build on existing monitoring and Fraser River stock assessment programs where feasible. A summary of stock status and habitat conditions for the index stocks would be prepared on an annual basis. Elaboration and revision of the monitoring program should be undertaken by the Fraser River ESD Task Force as a high priority activity. A preliminary list of candidate stocks in the Fraser River, specifically chosen to reflect the concerns articulated in the eight impact hypotheses, and the relative ease with which they could be monitored due to existing facilities or enumeration programs, would include:

Impact Hypothesis	Recommended Index Stock(s) or Location(s)
Prespawning mortality	Early Stuart/Horsefly River sockeye
Premature fry emergence	Seton Creek pink; Adams River/Nadina River sockeye
Winter flooding impacts	Vedder River pink and chum; Upper Pitt River sockeye
Stream temperature shifts	Nicola River/Deadman Creek coho and chinook
Stream discharge shifts	Nicola River/Deadman Creek coho and chinook
Limnological changes	Adams River sockeye in Shuswap Lake
General aquatic community changes	An interior salmon stream
Freshet timing	Chilko Lake sockeye; Seton Creek pink; Harrison River chinook

This activity could be included as part of a "Wild Salmonid Watch" program and designed as a component of an international salmonid conservation strategy (Maitland et al. 1981). This monitoring strategy was recently suggested by Regier and Meisner (1990) as a useful framework for assessing and monitoring global climate change impacts on salmonid stocks in the Northern Hemisphere. In view of the position of the Fraser River as the single most productive salmon river in the world, it would be vital to implement a well-designed Fraser River salmon monitoring program as a component of a future international monitoring effort.

Lakes within the Fraser River watershed may also provide opportunities for monitoring future climate change impacts. Since the thermal properties of lakes reflect an integrated response to climatic variables, it should be possible to compute annual heat budgets to make regional inferences about the severity of climate warming impacts. There is a gradation of possible monitoring strategies ranging from sophisticated (e.g., deployment of *in situ* thermistor chains) through to simple (e.g., estimates of the seasonal duration of ice cover) which would be sensitive to climate warming impacts. Lakes within the Upper Region of the Fraser (e.g., Stuart, Takla) should show pronounced reductions in the duration of seasonal ice cover if climate warming impacts materialize as predicted. There is also a recent data base available for the thermal properties of several important Fraser River sockeye lakes including Chilko,

Shuswap, and Quesnel lakes (J.Stockner, DFO, pers. commun.); limnological monitoring within these lakes should either be undertaken routinely, or else periodically in future in order to monitor climate change impacts in the Fraser River watershed.

In addition to regularly-scheduled monitoring activity, it would be desirable for the Biological Sciences Branch to address the specific impact concerns identified by the present study, as part of a climate warming research program. This activity would be facilitated by defining a climate change research program with a realistic staffing and funding allocation.

The experimental probing strategy suggested by Healey (1990) should integrate stock management, habitat management, and enhancement activites of DFO within specific watersheds. Additional feasibilty and design work will be required to refine this concept into specific projects that can be implemented within small sub-basins of the Fraser River watershed that are prone to climate warming impacts.

Although the present study focusses on salmon as elements of Fraser River aquatic ecology, anadromous and resident trout species, as well as the other non-salmonid members of the fish community, will also be influenced by climate change impacts. Some of the latter species may be more vulnerable to climate warming than salmon due to their protracted residence in freshwater habitats of the Fraser River watershed. In future, it may be advantageous to design monitoring or experimental programs jointly with provincial biologists since many of the concerns identified in this study are also applicable to provincial sport fish populations and resident fish species. Additionally, the present study focuses exclusively on freshwater impacts, when in fact, salmon spend most of their lives in the Pacific Ocean. It would be useful in future to conduct additonal analyses on possible global warming impacts on the marine life history stages of Fraser River salmon.

Specific habitat and stock management plans for the 15 habitat management areas within the Fraser watershed are currently under preparation. When these management plans have been completed, it will be useful to reconsider climate warming impacts in light of this expanded data base. Lastly, it should be emphasized that uncertainties associated with future climate change impacts on salmon in the Fraser River watershed will create obstacles for the implementation of sustainable fisheries development policies. Most of the Fraser River ESD Task Force objectives are predicated on a dubious assumption of a stable climatic regime. Where possible, fisheries managers should implement programs that will identify climate change impacts where and when they occur, and undertake decisions which maximize the available options for salmon production under future climatic conditions.

7. Conclusions

Coincident with a rise in the concentration of atmospheric CO_2 and other aerosols which contribute to the greenhouse effect, the global temperature record indicates an overall warming trend over the past century. However, the high variability of this record precludes attributing the warming trend to increases in greenhouse gases. Further temperature increases over the next decade or so may be sufficient to verify the greenhouse warming theory.

The greenhouse theory predicts that when atmospheric CO_2 doubles the pre-industrial concentrations by the middle of the next century, global mean temperatures will increase by 2-5°C and global precipitation will increase from an intensified hydrological cycle. The theory further predicts that distribution of temperature and precipitation changes will vary between regions, with alterations in temperatures increasing toward the poles. Resulting ecological responses will include altered species distributions, with populations along the margins of their geographic distributions being most susceptible to change.

As ectotherms, fish are sensitive to changes in ambient water temperature. While overall fish production rates might increase from the effects of global warming, fish distributions would likely change, species composition would shift, and invasions by exotic species would alter temperate freshwater fish communities. Most salmonid species would be affected negatively by climatic warming, particularly those which rely on freshwater habitats for juvenile rearing near the southern margin of their geographical range.

Within the Fraser River basin, salmon would face altered aquatic temperatures and precipitation-related changes in flow regimes. Major alterations in river hydrology would occur from earlier snow melt and increases in freezing elevations. As Fraser River flows are dominated by snowmelt, summer runoff may decrease and winter runoff may increase. The various stocks of the five species of salmon would be differentially vulnerable to climatic warming impacts, depending on their relative distribution in the Fraser basin, the relative duration of their freshwater residence, and the anticipated regional variation in climatic warming effects. A set of eight impact hypotheses developed for this report relate anticipated climatic effects to the five species of Pacific salmon in the watershed.

Early detection of climatic change impacts on salmon stocks could provide a basis for fisheries management response. Mitigating these effects does not appear feasible over the long term. Consequently, development of proactive and adaptive fisheries management policies currently provides the best opportunity to respond to climate-induced alterations in salmonid fisheries productivity.

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